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The Absorption of Sulfur Dioxide from Gases of Low Concentration

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THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION

A thesis submitted by

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I. INTRODUCTION

At the present time the absorption of sulfur dioxide in the pulping industry is involved mostly with the preparation of cooking liquors using gases containing relatively high concentrations of sulfur dioxide (15-35%). However, interest is growing in the absorption of sulfur dioxide from gases of much lower concentration—especially those resulting from the burning of spent sulfite cooking liquors. The sulfur dioxide concentration of such stack gases would be less than 2%, and a typical figure would be 0.75%. The pressures of pollution legislation and growing sulfur costs make more attactive the possibilities of removing and recovering the low-concentration sulfur dioxide in these stack gases. Absorption appears as a possible means of accomplishing this recovery.

Economic studies and efficient equipment design require a knowledge of the engineering aspects of the absorption process—that is, rate and equilibrium considerations and equipment operating variables. Although there exist sufficient data on equilibrium solubility and rate of absorption for the range of relatively high sulfur dioxide concentrations, extrapolation of these data to the lower concentration region involves uncertainties. Furthermore, since absorption of sulfur dioxide into water involves chemical reaction, it is possible that the absorption mechanism changes with concentration. The results of a low-concentration absorption study may not only serve the immediate need for industrial design data but may also throw additional light on the mechanism of sulfur dioxide absorption.

II. THE TWO-FILM THEORY OF ABSORPTION

A. ABSORPTION-DEFINITION AND TYPES OF EQUIPMENT

1. ABSORPTION DEFINED

Absorption is an important unit operation and has been practiced and studied for many years. Absorption may be defined as the mass-transfer operation in which a soluble constituent in a gas is removed by dissolving it in a liquid. The reverse operation is desorption or stripping.

It has long been appreciated that the rate and efficiency of absorption depend largely on the nature of the absorption mechanism and the manner in which the two phases are brought into contact. These considerations have resulted in the development of several definite types of absorption and desorption equipment.

2. INDUSTRIAL ABSORPTION EQUIPMENT

Absorption is carried out on an industrial scale in any of four distinct kinds of equipment. These are: (1) the spray tower, (2) the bubble or aeration tower, (3) the plate tower, and (4) the packed tower. Each is best suited for a particular gas-liquid system.

The spray tower involves the injection of the liquid phase as fine droplets moving at high velocity into a gas space, the gas being agitated by some means. The spray tower finds application in drying (evaporation) of solutions and humidification of gases. The bubble or aeration tower is the reverse of the spray tower in that the gas is the disperse phase and is introduced as a stream of fine gas bubbles moving through the liquid phase. The bubble tower is widely used for such operations as aeration of water or sewage.

The plate tower consists of a series of trays, one above another, arranged with gas upcomers and bubble caps to allow gas to move from the plate section below to the one above and liquid downcomers and liquor weirs to permit the flow of the liquid phase downward. The two phases are thus always in countercurrent flow, the contact between the phases being the bubbling of gas through the liquid and the falling film of liquid moving against rising gas.

The packed tower consists of a tower filled to the desired height with suitable packing. The packing offers a large surface area over which falling liquid may flow in layer-like fashion. A number of packings are available—rings, saddles, stacked tile, crushed stone or coke, etc.—all of which are for the purpose of creating a maximum of wetted surface and gas void volume. The packing is supported on a suitable support plate which permits separation of the liquid and gas. At the top of the tower a means is provided for distributing the liquor

over the top of the packing. Although either a full-scale plate or packed tower can be simulated on a laboratory scale, it is more common to use a packed tower for small-scale investigations.

Besides the plate and packed towers, at least three other types of small-scale equipment are sometimes employed in experimental studies. These are: (1) the wetted-wall column, (2) the porous plate, and (3) the wet-disk column. The wetted-wall column affords a moving liquid layer and the porous plate a stationary liquid layer. The wet-disk column is supposed to duplicate the liquor-gas flow relations of a packed tower (1).

B. THE TWO-FILM THEORY OF LEWIS AND WHITMAN*

1. ORIGIN AND CONCEPT OF THEORY

Observation of the performance of absorption equipment and the dependence of high absorption efficiency on interfacial area and relative motion of the two phases led Lewis and Whitman (1923) to suggest a two-film theory for the absorption process analogous to that for heat transfer (2). According to this theory: (1) The resistance to mass transfer resides in two films lying at the interface between

*Although film is the word in common usage it is probably not the same film encountered in heat-transfer work. Whether it is called a film, layer, region, zone, etc., the connotation is that of a short depth of liquid or gas at the phase interface.

the two phases, (2) the main bodies of the two phases are completely mixed at all times, (3) the films comprise more or less definite layers through which mass transfer occurs by diffusion, (4) equilibrium exists between the two films at the interface, (5) the rate of chemical reaction [where chemical reaction occurs] is infinite compared with rate of diffusion, (6) the individual film resistances are additive, and (7) the films are considered to be of such small bulk that accumulation of solute within the films is assumed to be negligible.

The driving force causing mass transfer is the difference in chemical potential between the two phases expressed generally in terms of partial pressure, p, in the gas and a concentration counterpart, c, in the liquid.

On the basis of the kinetic theory for gases and Maxwell's diffusion equation it is possible to derive an expression in which the molecular diffusion (in gases) is directly proportional to partial pressure gradient and inversely proportional to the pressure of the inert (nondiffusing) gas (3).

$$N_A = D_G P / RT p_B \, dp_A / dx_G \qquad (1)$$

The diffusional process is not entirely of a molecular nature. Eddy diffusion may occupy a very important role, and in most cases it is probably the predominant transfer means. Since eddy diffusion is

also proportional to the partial pressure gradient, it is possible to combine both into a transfer coefficient and a rate equation written for the gas film as

$$N_A = k_G (p - p_i) \qquad (2)$$

where the transfer coefficient would be equal to $D_G P / RTx_G p_{BM}$ if transfer were by molecular diffusion alone.

An analogous situation to that of the gas is assumed and a similar rate equation written for the liquid film.

$$N_A = k_L (c_i - c) \qquad (3)$$

where k_L equals D_L / x_L for the case of molecular diffusion. Under steady-state conditions the rate of mass transfer through both films must be equal, so

$$k_G (p - p_i) = k_L (c_i - c) \qquad (4)$$

The x terms (x_G and x_L) appearing in the definitions of k_G and k_L represent film thicknesses. This must not be construed as meaning that a film of discrete thickness x actually exists. Rather, the term represents the hypothetical thickness of a stationary film offering the same resistance to molecular diffusion as is actually encounted by the combined molecular and eddy diffusion resistances.

2. OVER-ALL TRANSFER COEFFICIENTS

No way is known of determining the values of $\underline{p}_i$ and $\underline{c}_i$, or the values of $\underline{k}_G$ and $\underline{k}_L$ as defined by Equation (4). For these reasons it is usual to determine over-all coefficients, $\underline{K}_G$ and $\underline{K}_L$, defined as

$$\underline{N}_A = \underline{K}_G (\underline{p} - \underline{p}_e) = \underline{K}_L (\underline{c}_e - \underline{c}) \qquad (5)$$

The terms $\underline{p}_e$ and $\underline{c}_e$ are equilibrium values, the $\underline{p}_e$ being the partial pressure of the gas in equilibrium with a solution having the same composition $\underline{c}$ as the main liquid stream. The term $\underline{c}_e$ is likewise the concentration of the solute in solution in equilibrium with a gas having the same solute partial pressure $\underline{p}$ as the main body of the gas stream.

The situation is made clear by reference to Figure 1. The curved line OA is the equilibrium curve relating the solubility of the solute gas over a range of partial pressures. Point B represents the situation existing at some plane in the tower cross section where the main body of the gas phase has solute partial pressure $\underline{p}$ and the main body of the liquor has a solute concentration $\underline{c}$. Point A indicates the actual equilibrium conditions existing at the phase interface where partial pressure $\underline{p}_i$ is in equilibrium with concentration $\underline{c}_i$. Point F is then the equilibrium value ($\underline{p}$, $\underline{c}_e$) and point E ($\underline{p}_e$, $\underline{c}$) relating the main body equilibrium partial pressure and concentration.

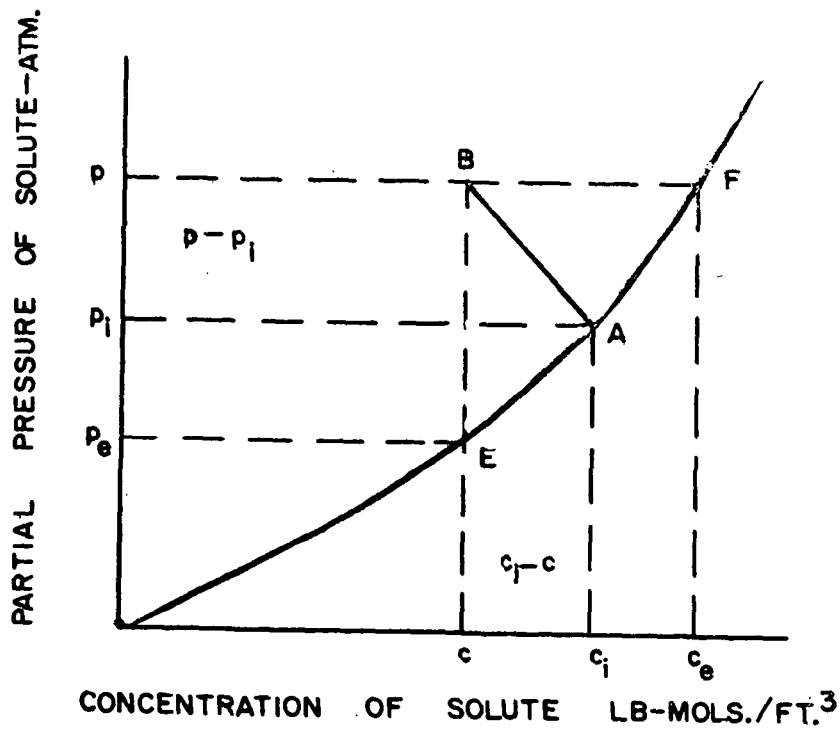


FIGURE 1. Graphical Representation of Concentration and Partial Pressure Driving Forces in Absorption.

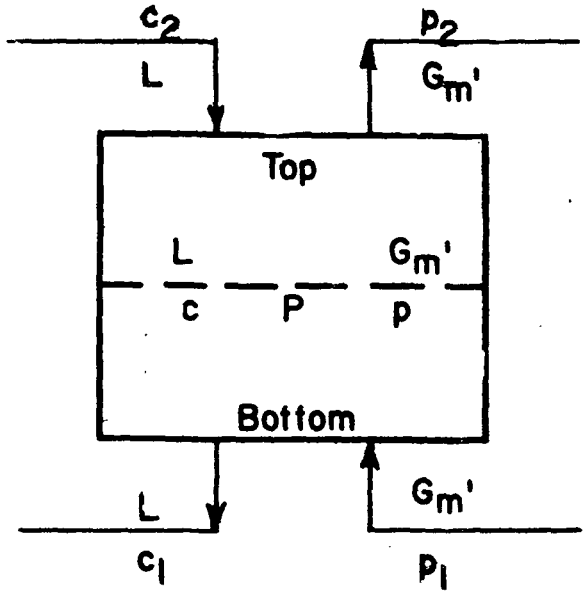


FIGURE 2. Diagrammatic Representation of Countercurrent Flow in a Packed Tower.

The over-all coefficient concept is valid only for those cases obeying Henry's law

$$\underline{H} = \underline{c}/\underline{p} \qquad (6)$$

but can be satisfactorily employed in those cases where the equilibrium line may be approximated over the range of interest by means of a straight line (7). In this case the Henry's law relation is defined as

$$\underline{H}' = (\underline{c} - \underline{c}_o)/\underline{p} \qquad (7)$$

where $\underline{c}_o$ is the intercept value of the straight line fit to the equilibrium curve.

Equations (4), (5), and (6) may be combined into an expression of the two-film concept as a sum of two film resistances (reciprocal conductances)

$$1/\underline{K}_L\underline{a} = 1/\underline{k}_L\underline{a} + \underline{H}/\underline{k}_G\underline{a} = \underline{H}/\underline{K}_G\underline{a} \qquad (8)$$

The terms in the equation are multiplied by the value $\underline{a}$, which is the effective interfacial mass-transfer area per unit volume of a packed tower. The over-all coefficients $\underline{K}_L\underline{a}$ and $\underline{K}_G\underline{a}$ are called "capacity coefficients" and have the units pound-moles per hour per cubic foot of tower volume per unit driving force. The size of the individual terms in Equation (8) expresses the fraction of the total resistance encountered in either film. For systems of very soluble gases the value of $\underline{H}$ will be very large and the ratio of $\underline{H}/\underline{k}_G\underline{a}$ to $1/\underline{k}_L\underline{a}$ may be

so great that $1/k_L a$ becomes significant. Such a system is often called "gas-film controlling." Where H is vanishingly small, as for a very slightly soluble gas (oxygen in water), the $H/k_G a$ term becomes insignificant and the liquid film is said to "control."

C. ABSORPTION TOWER DESIGN*

Equation (5) may be written in differential form for a unit tower cross section as

$$N_A a \, dh = K_G a \, (p - p_e) \, dh = K_L a \, (c_e - c) \, dh \quad (9)$$

In order to be integrated this equation must be combined with a material balance over the tower. Consider a packed tower operating with phase flows countercurrent to each other (Figure 2). The rate of gas flow into the tower is G'_M pound-moles of inert carrier gas per hour per square foot of tower cross section and the partial pressure of the solute is p_1 at the bottom (inlet) of the tower. The gas leaves the tower at the top with a partial pressure p_2. The average total pressure within the tower is P. For the case of lean gas mixtures, or where p_1 and p_2 differ by only a small amount, the volumetric gas rate through the tower remains essentially constant.

*This development is taken from the text by Sherwood and Pigford (3).

The liquor flow rate is $\underline{L}$ pounds of solute-free solvent (absorbent) per hour per square foot of tower cross section. The liquor enters the tower at the top with a concentration of dissolved solute of $\underline{c}_2$ pound-mols per cubic foot and leaves the tower at the bottom with a dissolved solute concentration of $\underline{c}_1$. The liquid is assumed to be nonvolatile (or the gas saturated) so that no liquid is lost by evaporation.

The material balance is then

$$\underline{L}/\rho(\underline{c}_1 - \underline{c}) = \underline{G}_m' [\underline{p}_1/\underline{P} - \underline{p}_1 - \underline{p}/\underline{P} - \underline{p}] \qquad (10)$$

and the differential form is

$$\underline{L}/\rho \, d\underline{c} = \underline{G}_m' \, \underline{P} \, d\underline{p}/(\underline{P} - \underline{p})^2 \qquad (11)$$

The liquid-side relations for Equations (9) and (11) can now be equated, and using the concentration driving force

$$L/\rho \, d\underline{c} = \underline{K}_L \underline{a}(\underline{c}_e - \underline{c}) \, d\underline{h} \qquad (12)$$

or

$$L/\rho \int_{\underline{c}_1}^{\underline{c}_2} d\underline{c}/(\underline{c}_e - \underline{c}) = \underline{K}_L \underline{a} \, \underline{h} \qquad (13)$$

For the general case, Equation (13) is solved by graphical integration on the basis of an operating diagram similar to the one shown in Figure 3. The operating line connects points B and D which correspond to the partial pressures of gas and concentrations of solute in the liquor at the top and bottom of the tower. The operating

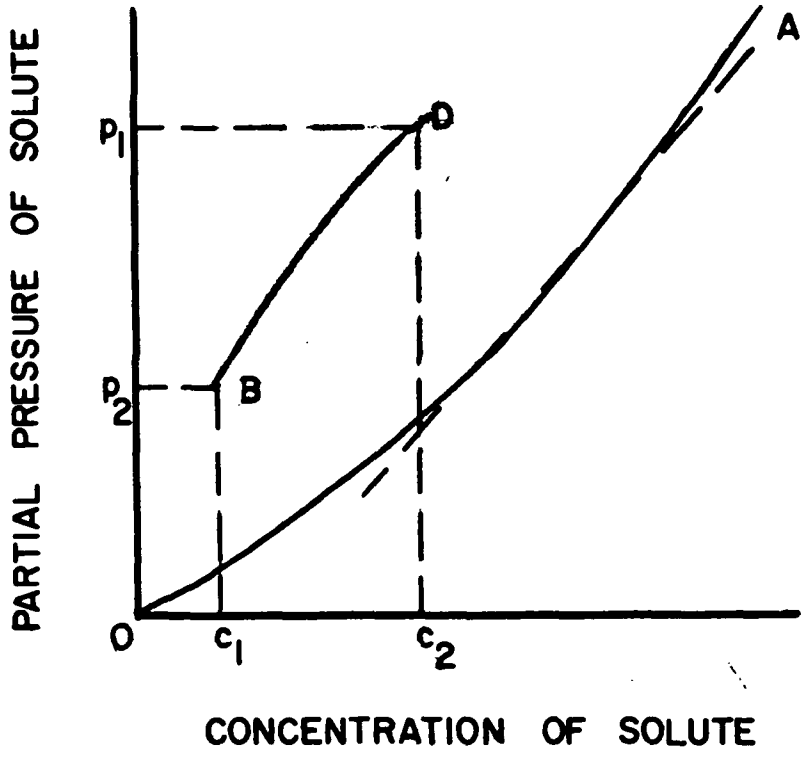


Figure 3 . Operating Diagram for a Typical Countercurrent Absorption Tower Operation.

line is a complex function of gas and liquor rate, arising from the material balance expression of Equation (10). However, for the case of lean gases the line is essentially straight and the slope is equal to $(\underline{L}P/\rho)/\underline{G}_m$ where $\underline{G}_m$ is the total molar gas flow rate.

For the special case where both the operating and equilibrium lines are straight over the range employed, Equation (13) reduces to the form

$$\underline{L}/\rho\ (\underline{c}_1 - \underline{c}_2) = \underline{K}_L \underline{a}\ \underline{h}(\underline{c}_e - \underline{c})\ \text{log mean} \qquad (14)$$

For the over-all coefficient in terms of the gas film the development is

$$\underline{G}_m \, ' \, \underline{P}/(\underline{P} - \underline{p})^2 \, d\underline{p} = \underline{K}_G \underline{a} \, (\underline{p} - \underline{p}_e) \, d\underline{h} \qquad (15)$$

$$\underline{G}_m \, ' \, \underline{P} \int_{\underline{P}_1}^{\underline{P}_2} d\underline{p}/(\underline{p} - \underline{p}_e) \, (\underline{P} - \underline{p})^2 = \underline{K}_G \underline{a} \, \underline{h} \qquad (16)$$

and for the case of straight operating and equilibrium lines

$$\underline{L}/\rho \, (\underline{c}_1 - \underline{c}_2) = \underline{K}_G \underline{a} \, \underline{h}(\underline{p} - \underline{p}_e) \text{ log mean} \qquad (17)$$

D. THE CONCEPT OF THE TRANSFER UNIT (HTU)

Thus far only the individual and over-all mass-transfer coefficients have been considered. There is another convenient means of expressing the ease of absorption—the height of a transfer unit, abbreviated as $\underline{H}$. This term was introduced by Chilton and Colburn (4), and is defined (for lean gas mixtures) as

$$\underline{H}_{OG} = \underline{G}_M / \underline{K}_G \underline{a} \, \underline{P} \qquad (18)$$

and

$$\underline{H}_{OL} = \underline{L}/\rho \, \underline{K}_L \underline{a} \qquad (19)$$

The height of a tower is given by

$$\underline{h} = \underline{H}_{OG} \underline{N}_{OG} \qquad (20)$$

$$\underline{h} = \underline{H}_{OL} \underline{N}_{OL} \qquad (21)$$

where $\underline{N}_{OG}$ AND $\underline{N}_{OL}$ are the definite integrals

$$\underline{N}_{OG} = \int_{\underline{P}_1}^{\underline{P}_2} d\underline{p}\, \underline{p}_{BM}/(\underline{p} - \underline{p}_e)(\underline{P} - \underline{p}) \qquad (22)$$

$$\underline{N}_{OL} = \int_{\underline{c}_1}^{\underline{c}_2} d\underline{c}/(\underline{c}_e - \underline{c}) \qquad (23)$$

III. SURVEY OF LITERATURE ON ABSORPTION

For reasons which are discussed in SECTION V, Design of Experiments and Experimental Procedures, the packed tower is chosen for carrying out the absorption experiments in this thesis. For this reason literature pertaining to packed-tower absorption only will be considered in this section.

A. ANALYSIS AND INTERPRETATION OF PACKED-TOWER ABSORPTION DATA

The approach used in interpreting experimental results from packed-tower absorption research is usually to determine the individual film coefficients ($\underline{k}_L\underline{a}$ and $\underline{k}_G\underline{a}$) or transfer units and study the manner in which these coefficients are affected by such variables as phase flow rates, temperature, molecular diffusivity, viscosity, surface tension, etc. A number of methods for determining individual film coefficients have been suggested and employed. In general the methods involve either (1) choosing a system or conditions enabling the cancellation of one film resistance so that the over-all coefficient approaches or becomes identical with an individual coefficient, or (2) separating and evaluating the two individual films employing the additive property required by the two-film theory. Table I sets forth briefly these methods and the criteria for their use.

TABLE I

SUMMARY OF METHODS WHICH HAVE BEEN USED FOR EVALUATION OF INDIVIDUAL FILM COEFFICIENTS

Method	Film Determined	Principle	Criteria	Remarks	References
1. Employing a pure gas	Liquid	If a pure gas is employed (no inerts) then the slope of the $-(k_L a/k_G a)$ tie line will theoretically be zero (horizontal) and the gas-film resistance zero.	$k_L a$ independent of gas rate below loading velocity.	Since the driving force is so great, close approach to equilibrium is quickly attained and therefore demands shallow packing (a few inches), and this introduces a large end effect which must be accurately determined.	This method has been used in batch experiments. No reference to tower experiments has been found.
2. Employing a pure liquid	Gas	If a pure liquid is used and the tower is operated in reverse of absorption (as a stripping or humidification tower) the $-(k_L a/k_G a)$ tie line should be infinite (vertical) and the liquid-film resistance zero.		The driving force is so great that close approach to equilibrium is quickly attained and therefore shallow packing (a few inches) must be used. This introduces a large end effect which must then be accurately determined. Because of energy changes during evaporation, the temperature at the evaporating film is lower than in the main body of liquid. Heat transfer through the packing may contribute also to errors.	(10, 11, 12, 13, 14, 15)
3. Employing an insoluble gas	Liquid	If a gas of low solubility is absorbed (or desorbed) from a liquid then the slope of the $-(k_L a/k_G a)$ tie line should approach zero (horizontal) and the gas-film resistance approach zero.	The $K_L a$ value is independent of gas rate below the loading velocity.	This method is probably the most valid means of measuring liquid-film resistance. The popular solute gases are oxygen, carbon dioxide, and hydrogen. The desorption of oxygen has been suggested as a means of "calibrating" absorption towers (16, 17). The method is somewhat insensitive if the packed height is greater than 2 feet.	(17, 18, 19, 20, 21, 22, 23)
4. Employing a very soluble gas	Gas	If a gas of high solubility is absorbed into a liquid the slope of the $-(k_L a/k_G a)$ tie line should approach infinite (vertical) and the liquid film resistance approach zero.	A plot of $1/K_G a$ vs. $1/G^n$ should pass through the origin.	Probably no system exists which meets the conditions sufficiently close. The system ammonia-water was long thought to exhibit no liquid-film resistance but that appears now to be untrue (3). Even the absorption of acetone into water exhibits an appreciable liquid-film resistance (24).	(24, 25, 26, 27, 28, 30, 31, 32, 33, 34)
5. Employing a rapid, irreversible reaction within the liquid film	Gas	If a rapid, irreversible chemical reaction occurs the effective liquid-film resistance should approach zero.	If the Satta-Sherwood approach is used, a plot of $K_G a$ vs. normality of absorbent should show a positive slope becoming horizontal beyond a "critical" concentration. (11).	Hatta (31) as cited in (3) has developed a theory concerning absorption with chemical reaction, one consequence of which is the prediction that some concentration of absorbent exists (say H_2SO_4 in the absorption of NH_3) above which the reaction occurs at the interface and the liquid-film resistance disappears. This technique is somewhat questionable and contradictory results have been obtained.	(10, 29, 32, 33)

TABLE I (cont.)

SUMMARY OF METHODS WHICH HAVE BEEN USED FOR EVALUATION OF INDIVIDUAL FILM COEFFICIENTS

Method	Film Determined	Principle	Criteria	Remarks	References
6. Employing the graphical intercept method	Gas and liquid	An expression can be developed (see Note for Table I)) of the form $1/K_La = 1/\alpha L^m + H/\beta G^n L^q$ which may be simplified to $1/K_La = A + B/G^n$ for some constant level of liquor flow rate. A power of n exists for which a straight line plot can be obtained on rectangular coordinate paper. The intercept at $1/G^n$ 0 solves the value of B.	The plot of $1/K_La = A + B/G^n$ is a straight line. The value of H must be constant.	Absorption tower data are not ordinarily of high precision so the method offers low sensitivity. This method has been used frequently and remains as probably the best method for systems displaying appreciable resistance in both films.	(6, 7, 24, 32, 34, 35, 36, 37, 50)
7. Employing a solubility depressant to alter the slope of the equilibrium solubility line.	Gas and liquid	The relationship between the individual film coefficients and the over-all coefficient, for systems obeying Henry's law is $1/K_La = 1/k_La + H/k_Ga$ (Equation 20). If the addition of a chemical agent alters H, then the two expressions may be solved for the values of k_La and k_Ga.	The addition of the chemical agent must not affect either film coefficient.	This method does not appear to have been applied to absorption though it has been attempted in the field of distillation in packed towers. The most serious consideration is that relating to disturbance of the film resistances due to secondary chemical effects.	(45)

Note for Table I

Method 6, the graphical intercept method, is derived from the fact that the variation of liquid- and gas-film coefficients may be represented as functions of the phase flow rates $k_La = \alpha L^m$ and $k_Ga = \beta G^n L^q$. These equations may be combined with Equation 8 to give the expression $1/K_La = 1/\alpha L^m + H/\beta G^n L^q$. If L is constant the equation becomes $1/K_La = A + B/G^n$. Solution for the value of the power n requires trial and error plotting. The assumption is made that H remains constant through the tower and thus restricts the application of the method to those cases in which Henry's law is followed. It was pointed out that it is sufficient for the equilibrium line relating c and p to be straight but it is not necessary that this line pass through the origin. The Henry's law line becomes a modified Henry's law defined as $H' = c - c_o/p$, where c_o is the intercept of the straight line with the abscissa.

It is interesting to note that this method has also been employed in connection with liquid extraction columns (55).

B. CHARACTERIZATION OF THE PACKED TOWER AS A RESEARCH INSTRUMENT

Small-scale absorption towers are capable of giving satisfactory data if attention is given to the factors which contribute most to variability of tower performance. Three aspects of experimental towers which greatly affect the ability to translate data to full-scale towers are (1) flow effects, (2) extra-packing absorption effects, and (3) the effective interfacial transfer area a.

Flow effects which affect the uniformity of the liquid-gas distribution include channeling of either liquid or gas, loading or hold-up of liquor by the packing, and tendency of the liquor to move toward the tower wall (5,9).

The extra-packing effects are (1) the absorption at the ends of the tower, (2) the coning of the liquor flow at the top of the packing, and (3) the absorption at the tower wall (wall effect).

End effects can be minimized by proper design and are corrected for by making performance tests on the tower. At least three methods of determining end effects have been employed. These include:

(1) Calibration by means of oxygen desorption (7,17)

(2) Varying the packing height (13,14, 15,27)

(3) End-sampling at the top and bottom of the packing (17,20).

Wall effects are minimized by choosing a tower diameter to packing diameter ratio large enough to make the contribution of the wall effect negligible. A ratio of at least 8:1 is recommended (28).

The value of a, the effective interfacial area per unit of packed volume, is a complicated function of many variables among which the important ones are packing size, shape, how dumped or stacked, and the liquor and gas flow rates. There has been accumulated a large amount of comparison data between different packings (3,48) and translation of data from an experimental tower to a full-scale tower can usually be done with reasonable accuracy.

A knowledge of the interfacial area is of importance in the attempt to separate and analyze over-all coefficients. For that reason a number of investigators have attempted to determine the value of a for different packings and its variation as a function of gas and liquor rate.* Shulman and DeGouff (46) have suggested combining the correlation for k_G presented by Taecker and Hougen (12) for the evaporation of water from porous rings with those of $k_G a$ obtained by Fellinger (16) for the system ammonia-water. Such a combination assumes a negligible liquid-film resistance in the ammonia-water system.

*Shulman and DeGouff give an extensive review of the literature (46).

C. SUMMARY OF THE LITERATURE ON PACKED-TOWER ABSORPTION

The literature on packed tower absorption is extensive and over the years there has been a gradual development of more or less standardized methods of procedure. Since the approaches and objectives of the investigators vary, it is difficult to compare their results. Table II presents a summary of the literature on packed-tower absorption with accompanying explanatory notes.

On the basis of a review of the absorption literature the following general conclusions may be drawn:*

1. The individual liquid-film coefficient varies as some power function of the liquor rate. Values of power between 0.6 and 1.0 are reported. The individual liquid-film coefficient is independent of gas flow rate below the loading velocity.

2. The individual gas-film coefficient varies as some power function of the gas rate. Values of power between 0.5 and 0.8 are reported. The individual gas-film coefficient is a function of liquor rate, probably because of the contribution of liquor rate to the interfacial area. It is a power function and the value of the power lies between 0.25 and 0.40.

*These conclusions are drawn on the results of datower experiments carried out over the temperature range of approximately 35 to 120°F.

3. The individual liquid-film coefficient is greatly affected by temperature. The temperature function is reported to be $\underline{k}_L \underline{a}\, \underline{e}^{0.023\underline{T}}$ where $\underline{T}$ = °C. The gas film coefficient varies but slightly with temperature.

4. The liquid-film coefficient is independent of packed height. There is some disagreement concerning the effect of height on the gas film.

D. PREVIOUS WORK IN THE ABSORPTION OF SULFUR DIOXIDE

Haslam, Hershey, and Kean (34) studied the absorption of sulfur dioxide into water in a 3-inch glass tube wetted-wall tower three feet tall. The gas used was air-sulfur dioxide. They found $\underline{k}_G$ to vary with the 0.8 power of gas velocity and $\underline{k}_L$ to be independent of gas velocity. Over the temperature range of 10-50°C. they found the gas-film coefficient to vary inversely as the 1.4 power of the absolute (K°) temperature and the liquid-film coefficient directly as the fourth power of the absolute (°K.) temperature.

Haslam, Ryan, and Weber (38) absorbed sulfur dioxide into water in an 8-inch inside diameter (I.D.) tower, packed with 1-inch coke and with 3-inch spiral tile. They found both liquid and gas film resistance appreciable. (See also notes of Table II.)

TABLE II

SUMMARY OF PREVIOUS ABSORPTION WORK DONE ON PACKED TOWERS

The references cited below represent only work done in packed towers. Other work carried out in absorption equipment using grids, spray sections, etc., are not reported because of the difficulty of relating the information to that obtained in a commercial-type packed tower packed with 1-inch ceramic Raschig rings used in this thesis investigation.

Note	Approach	System	Tower Details				Temperature, °F.	G, lb./hr.ft.^{2}	L, lb./hr.ft.^{2}	Correlation Obtained	Reference	Date
			I.D., inches	Packing	Packed Height, inches	End Effect inches						
a	Vaporization of pure liquid	Air - H_2O	Rectangular area .555 ft.	1-inch Raschig rings	6	—	74-76	625 - 2410	1080	$k_G a = 0.107\ G^{0.95}$	Johnstone and Singh (10)	1937
b	Vaporization of pure liquid	Air - methanol Air - benzene Air - toluene	3.6	5/8-inch porcelain Raschig rings	5	—	—	250 - 800	2300	$k_G a \cdot p_{BM}$ correlates with $G^{0.70}$	Sherwood and Holloway (11)	1940
c	Vaporization of pure liquid	Air - H_2O	20	1.5-inch ceramic rings	8	3	—	20 - 1830 230	390 - 410 168 - 6100	$k_G a$ varies as $G^{.63}$ and $L^{\frac{1}{3}}$	Sherwood and Holloway (11)	1940
d	Vaporization of pure liquid	Air - H_2O	4	1-inch carbon Raschig rings	6, 9, & 12	7.2	95 - 156	487 - 1018	540 - 2620	$h_G a_h = 1.78\ G^{0.7}\ L^{0.007}\ e^{0.0023t}$ $k_L a = 0.82\ G^{0.7}\ L^{0.5}$ t, °F	McAdams, Pohlenz, and St. John (13)	1949
e	Vaporization of pure liquid	Air - H_2O	5.6	1/2-, 1-, & 2-inch porous clay Raschig rings	Variable	—	95 - 105	18 - 1620	—	$K_G a$ varies as $G^{.59}$	Taecker and Hougen (12)	1949
f	Vaporization of pure liquid	Air - water Air - methanol Air - benzene Air - ethyl butyrate	8	1-inch carbon Raschig rings	4, 6, & 12	2.2	68 - 108	140 - 500	435 - 5000 1600 for most runs	$k_G a \cdot p_{BM} = 0.479\ G^{0.72}\ D_G^{0.15}$	Surosky and Dodge (14)	1950
g	Vaporization of pure liquid	Air - H_2O	4	1/2-inch glass and brass spheres	8	4.5	—	—	—		Weisman and Bonilla (15)	1950
h	Absorption of slightly soluble and moderately soluble solutes	CO_2 - H_2O SO_2 - H_2O	3.5	Small, glass Raschig rings .40 x 0.25 in.	34		43-49 (CO_2) 66 (SO_2)	2.97-4.81 L/min. 1.67-4.53 L/min.	6.4-9.2 L/min. .20-1.04 L/min.	K_L varies as $L^{0.6}$	Cantelo, Simmons, Giles, and Brill (18)	1927
i	Desorption slightly soluble solute	CO_2 - H_2O	10	1-inch carbon Raschig rings	54-56		69-79	56-313	770-9120	$K_L a = 0.021\ L^{0.88}$	Sherwood, Draemel, and Ruckman (19)	1937
j	Desorption of slightly soluble solute	CO_2 - H_2O H_2 - H_2O	20	1.5-inch ceramic Raschig rings	8		60-100	230	2000	$k_L a \propto e^{0.023t}$ t = °C. $k_L a \propto \sqrt{D_L}$	Sherwood and Holloway (20)	1940

TABLE II (Continued)

SUMMARY OF PREVIOUS ABSORPTION WORK DONE ON PACKED TOWERS

Note	Approach	System	Tower Details				Temperature, °F.	G lb./hr.ft.^{2}	L lb./hr.ft.^{2}	Correlation Obtained	Reference	Date
			I.D., inches	Packing	Packed Height, inches	End Effect, inches						
k	Desorption of slightly soluble solute	$O_2 - H_2O$	20	1/2-, 1-, 1.5-, and 2-inch Raschig rings	6-49	Determined but not reported	41-99 75 66-75	230 38-1400 100-230	2000 2000 300-32,000	$k_La \propto e^{0.023t}$ t = °C. k_La is independent of gas rate below loading velocity $\frac{k_La}{D_L} = a'(L/\mu)^{1-n'}(\mu/\rho D_L)^{1-s}$	Sherwood and Holloway (20)	1940
l	Desorption of slightly soluble solute	$OO_2 - H_2O$	30 in. sq.	2x2x1/16-inch steel Raschig rings	86		60-70	19-368	13,200-56,000	$(H.T.U.)_{OL} \propto L^{0.25}$	Cooper, Christl, and Peery (21)	1941
m	Desorption of slightly soluble solute	$O_2 - H_2O$	15 in. sq.	1-inch Raschig rings and drip point grid tile			77	570	4000-20,000	Results agree with Sherwood and Holloway for K_La variation in L and T	Molstad and Parsly (22)	1942
n	Desorption of slightly soluble solute	$O_2 - H_2O$ $OO_2 - H_2O$	6	1/2-inch Raschig rings	47		70-80	277-615	100-5000	K_La varies as $L^{.78}$	Deed, Schutz, and Drew (23)	1947
o	Desorption of slightly soluble solute	$O_2 - H_2O$	4 14	1-inch Raschig rings	24 48	- -	70	120 60	970-16,000 2000-15,000	$K_La \propto L^{0.75}$	Vivian and Whitney (17)	1947
p	Desorption of slightly soluble solute	$O_2 - H_2O$	8	1-inch Raschig rings	24	0	62	355	960-11,000	K_La $L^{0.75}$	Whitney and Vivian (7).	1949
q	Absorption of slightly soluble solute	$Cl_2 - H_2O$	6	1-inch coke	48		38-50	47-116	1900-6700	$K_La \propto L^{0.8}$	Adams and Edmonds (39)	1928 and 1937
r	Absorption of slightly soluble solute	$Cl_2 - H_2O$	4 14	1-inch Raschig rings	24 48	3 -	70	61.5-653 40.5-77	910-28,000 1000-14,500	K_La independent of G $\quad K_La \propto T^6$ $K_La \propto L^{0.6} \quad (K_La)_f \propto L^{0.56}$	Vivian and Whitney (17)	1947
s	Absorption of moderately soluble solute	$SO_2 - H_2O$	8	1-inch coke	30	-	59-122	-	-	$K_Ga \propto G^{0.80}$	Haslam, Ryan, and Weber (38)	1923
t	Absorption of moderately soluble solute	$SO_2 - H_2O$	18	3-inch spiral, acidproof tile	-	-	38-127	34-140	150-3600	$K_La \propto L^{0.89}$	Adams (35)	1933
u	Absorption of moderately soluble solute	$SO_2 - H_2O$	8	1-inch ceramic Raschig rings	24	0	50-90	55-851	920-11,700	At 70° $k_La = 0.044\ L^{0.82}$ $\quad K_Ga = 0.028G^{0.7}L^{0.25}$	Whitney and Vivian (7).	1949
v	Absorption of moderately soluble solute	UF_6 - oil	3	1/4-inch Monel Raschig rings	48	-	55	35.5-94.6	2015-5215	$K_Ga = 0.036G^{0.8}$ at L = 4000	Landau, Buchenall, Joris, and Elgin (36)	1948
w	Absorption and desorption of very soluble solute	$NH_3 - H_2O$	4	9-16 mm. household coke	42	-	66-84	148-507	3230		Sherwood and Kilgore (25)	1926
x	Absorption of very soluble solute	$NH_3 - H_2O$	-	Various solid packings	-	-	-	-	-	K_Ga varies as $G^{0.7}$ and $L^{1/3}$	Kowalke, Hougen, and Watson (26)	1928
y	Absorption of very soluble solute	$NH_3 - H_2O$	10	1-inch carbon Raschig rings	19-31	0	54	55-530	440-2050	$K_Ga = 0.046G^{0.5}L^{0.4}$	Borden and Squires (27)	1937

TABLE II (Continued)

SUMMARY OF PREVIOUS ABSORPTION WORK DONE ON PACKED TOWERS

Note	Approach	System	Tower Details				Temperature, °F.	G lb./hr.ft.^{2}	L lb./hr.ft.^{2}	Correlation Obtained	Reference	Date
			I.D., inches	Packing	Packed Height, inches	End Effect, inches						
s	Absorption of very soluble solute	NH_3 - H_2O	3, 6, and 11.3	Various solid packings - spheres and crushed stone	48 96	-	72-82	382-567	484-585	K_Ga varies as $G^{0.7}$ and $L^{1/3}$	Chilton, Duffey, and Vernon (28)	1937
aa	Absorption of very soluble solute	NH_3 - H_2O	10	1-inch carbon Raschig rings	16	0	-	67-670	657-4020	K_Ga varies as $G^{0.55}L^{0.36}$	Doherty and Johnson (29)	1938
ab	Absorption of very soluble solute	Acetone-H_2O	10	1-inch ceramic Raschig rings	216	-	64-73	146-502	135-715	$K_Ga = \frac{1}{\frac{23}{L^{0.95}} + \frac{30}{G^{0.8}}}$	Othmer and Scheibel (24)	1941
ac	Absorption of very soluble solute	NH_3 - H_2O	-	3/8-, 1/2-, 1-, 1 1/2- and 2-inch ceramic Raschig rings	-	-	-	200-1000	500-4500	$k_Ga = 0.0134G^{0.8}L^{0.33}$ [due to Whitney (16)]	Fellinger	1941
ad	Absorption of very soluble solute	NH_3 - H_2O	12	1/2-, 1-, and 1 1/2-inch carbon Raschig rings	48	-	73-93	100-1000	160-11000	$1/K_Ga = 1/vG^nL^m + 1/He\,L^r$ $k_Ga = 0.127G^{0.77}$ L = 500 $k_Ga = 4.12L^{0.20}$ (G = 500)	Dwyer and Dodge (30)	1941
ae	Absorption of very soluble solute	Acetone - H_2O	4, 6, and 10	3/8-, 1/2-, 3/4-, and 1 1/4-inch Raschig rings	45-64	-	-	240-520	-	K_La varies as $L^{0.8}$ $k_Ga = 0.0102d^{0.655}L^{0.659}d-0.85_G{}^{0.8}$ $k_Ga = 0.025L^{0.62}(G/x'm')^{0.8}$	Hutchings, Stutzman, and Koch (32)	1949
af	Absorption of very soluble solute	Ethanol - H_2O	15 1/4-in. square	1-inch Raschig rings	24	-	-	270-800	300-7000	$K_Ga \propto L^{.87}$ $K_Ga \propto G^{0.6 - 0.8}$	Molstad and Parsly (44).	1950
ag	Absorption of very soluble solute	NH_3 - H_2O Ethanol - H_2O Methanol - H_2O Acetone - H_2O	12	1-inch Raschig rings	24	-	-	80-1000	500-3000	K_Ga varies as $G^{0.8}$	Houston and Walker (37)	1950
ah	Absorption with rapid, irreversible reaction at liquid interface	NH_3 - dil. H_2SO_4 (3.5 - 4.5 N)	10	1-inch carbon Raschig rings	16	-	77	211	1650-1850	K_Ga varies as 0.63 independent of L	Doherty and Johnson (29)	1938
ai	Absorption with rapid, irreversible reaction at liquid interface	Cl_2 - H_2O	-	1-inch Raschig rings	-	-	-	-	-	$K_Ga(p_{BM}) \propto G^{.7}L^{1/3}$	Vivian (40)	1947
aj		CO_2 in dil. NaOH CO_2 in dil. Na_2CO_3	5.9 12	1/2-inch Raschig rings 3/8-, and 1-inch Raschig rings	35	-	68-117	-	-	k_Ga varies as $G^{0.8}$	Van Krevelen and Hoftizer (33)	1948
ak	Absorption with rapid, irreversible reaction at liquid interface	Cl_2 - dil. $FeSO_3$ Cl_2 - dil. Na_2CO_3 Cl_2 - dil. NaOH	6	1/2-inch ceramic Raschig rings	66	-	60-80 72 98-111	100-244 219-240 120-208	2980-6350 3670-4550 5560-5850	$H_{OG} \propto G^{0.96}/L^{0.65}$	Riggle and Tepe (32)	1950

Notes for Table II

a Johnstone and Singh were primarily interested in the effect of high gas velocities on reduction of film resistance and so employed a G/L ratio considerably higher than is normally encountered in packed towers. These rates, for the most part, correspond to velocities above those necessary for loading in the conventional packed tower. This may explain the high power function of G (0.95) in their correlation.

b Sherwood and Holloway report the results of an investigation by Mehta and Parekh (42) on the effect of gas diffusivity on $k_G a$. Although the range of diffusivities for the four liquids vaporized was three-fold, the $k_G a$ values varied only about 20%. They correlated $k_G a$ to the 0.17 power of diffusivity.

d The authors report that the apparent resistance of the liquid film was 27-46% of the total for both films and the tie-line slope (usually assumed to be infinite) ranged from 1.2 to 2.7. They report a correlation at 115°F.

$$\frac{(h_L a)}{(k_G a_M)} = 0.092 \cdot L^{0.43}$$

e Teecker and Hougen used packings made of porous ceramic material capable of holding liquid water within the pores. They report that their tower contributed no apparent end effect.

f Surosky and Dodge show that at a gas rate of 197-203 lb./hr.ft.^{2}, $K_G a$ values are unaffected by liquor rates over the range 1000-5000 lb./hr.ft.^{2}. Redumping the packing did not alter the values obtained. They were able to get good agreement between packed heights of 4.6 and 12 inches. Probably the most significant result of their work is an indication of a small effect of diffusivity on gas-film mass transfer. They found $k_G a$ to be correlated to $D^{0.16}$ which agrees well with Mehta and Parekh (42) who found $D^{0.17}$.

g The purpose of this work was the computation of effective wetted area in a packed tower. They compared the coefficients obtained from porous packing to those of impervious material.

h Unfortunately the reporting of the data in this work does not conform to present-day practice, and it isn't possible to compare the data with later work. The flow rates are expressed as liters per minute (L/min.). Sherwood, Draemel, and Ruckman (12), reviewing this work, state that Cantelo's $K_L a$ value for CO_2 - H_2O at L = 10,000 is 27 (only 37.5% of the value obtained by Sherwood, et al.), and the slope of Cantelo's plot of $K_L a$ vs. L is 0.60.

i Sherwood, Draemel, and Ruckman found no effect of gas velocity on $K_L a$ over a range of 57-314 lb./hr.ft.^{2} The ratio of driving forces at inlet and exit were approximately 10:1. They found a strong temperature effect on $K_L a$ but did not attempt an evaluation. The authors used the correlation obtained, in conjunction with $k_G a$ values obtained for the NH_3 - H_2O system (26) to estimate $K_L a$ values for SO_2 - H_2O. Their estimation agreed with Adams' data (25) within 20%.

j The use of hydrogen and oxygen represent purely physical absorption systems. Carbon dioxide reacts with water but only to the extent of about 1%. It is therefore very nearly the same as physical absorption. The values for $k_L a$ for CO_2 and O_2 are almost the same.

k Sherwood and Holloway investigated and compared the effect of using a variety of packing materials. Besides the 3/8-, 1/2-, 1-, 1 1/2-, and 2-inch Raschig rings, they also studied 1/2-, 1-, and 1 1/2-inch Berl saddles and 3-inch tile. Results with all were correlated with the same equation

$$\frac{k_L a}{D_L} = a'(L/\mu)^{1-n'}(\mu/\rho D_L)^{1-s}$$

For 1-inch Raschig rings the correlation becomes $\frac{k_L a}{D_L} = 280(L/\mu)^{0.65}(\mu/\rho D_L)^{0.5}$

Notes for Table II (cont.)

l The liquor rate used (13,200-56,000 lb./hr.ft.^{2}) is above that ordinarily obtainable with ceramic ring packing. Their gas rate is within the range of usual experiments. These results show some effect of gas rate on $K_L a$--in fact increasing by 100% for a five-fold increase in gas rate. The authors suggest that since the liquor rate, when converted to lineal rate, exceeded that of the gas by several times, probably there was circulation of gas within the tower, and computation of coefficients on a basis of tower end conditions is not justified.

n This work is interesting because it makes a comparison between rectification and desorption in packed columns. These workers compared the $(H.T.U.)_L$ values for the rectification of isopropanol with those of the desorption of CO_2 from water. The values for the isopropanol were converted to those of CO_2 at the same temperature (25°C.) and were found to agree fairly well.

o Vivian and Whitney made oxygen desorption runs as a means of checking the performance of the two towers. The values obtained (6 runs in the 4-inch tower and 4 in the 14-inch tower) check each other and also Sherwood and Holloway's data (20).

p Whitney and Vivian made six oxygen desorption runs and found excellent agreement with Sherwood and Holloway. It was therefore assumed that the tower exhibited no apparent end effect.

q Adams and Edmonds recalculated the solubility of chlorine in water as a function of temperature and pressure and with these solubility data they recomputed the absorption coefficients obtained by Gilmour, Lockhardt, and Welcyng (41) in 1928.

r The values of $K_L a$ obtained in the two towers used (4- and 14-inch I.D.) differed by approximately 20%. When the values were recomputed as pseudocoefficients the data of the two towers were well correlated by a single line.

s Haslam, Ryan, and Weber operated their 8-inch tower alternately as a (1) spray tower, (2) wetted-wall tower, (3) spiral tile tower, and (4) packed tower. Comparison of the correlations obtained shows

Wetted-wall tower $1/k_a = 0.25/V^{.8} + 0.83$

Spray tower $1/k_a = 0.11/V^{.8} + 0.83$

Spiral-tile tower $1/k_a = 0.052/V^{.8} + 0.40$

Packed tower $1/k_a = 0.10/V^{.8} + 0.21$

Besides the 0.8 power function of $K_G a$ with gas velocity, it was also determined that the liquid film is independent of gas velocity. Their data indicate a decrease in $K_G a$ with increase in temperature.

t Adams employed resistance terms rather than coefficients. Besides the variation of $R_L \propto 1/L^{0.89}$, he reports that there is only slight effect from gas velocity. The over-all resistance decreases with increase in temperature.

u Whitney used burner gas from a sulfite mill. These data are the most extensive and consistent reported to date. When the data are computed as pseudocoefficients and the liquid-film coefficients separated, they agree quite well with coefficients predicted from oxygen desorption data.

v Their absorbent was heavy oil. Separation of film coefficients was accomplished by means of the graphical intercept method.

w Sherwood and Kilgore obtained data on absorption and desorption in the NH_3 - H_2O system and found that the data fell upon the same line.

x They report an almost negligible effect of temperature on the absorption coefficients.

Notes for Table II (cont.)

y Since the results of Borden's and Squires' work at both 19- and 31-inch packed heights were in good agreement, it was assumed that end effects were negligible for their tower.

z Chilton, Duffey, and Vernon found that for a particular packing, K_Ga increases as the 0.5 - 0.6 power of the surface per unit volume and that tower diameter has no effect if an 8-1 ratio to packing diameter is maintained. Sherwood and Holloway (11) fitted a relation of the form $K_Ga = \gamma G^{0.8}$ to their data. They found effect of temperature to be negligible. They made runs with and without presaturation and found no difference. Also redumping the packing had no effect.

aa Doherty and Johnson used the same tower as did Borden and Squires (27) and ran NH_3 absorption in both water and 3.5 - 4.5 N sulfuric acid. Their water data were as much as 20% higher than the corresponding data of Borden and Squires. Most surprising was the apparent independence of K_Ga values from liquor rate. The strength of acid used was the initial solute concentration of Hatta (31).

ab The equation presented-- $K_Ga = \dfrac{1}{\frac{23}{L^{0.95}} + \frac{30}{G^{0.8}}}$ -- would seem to indicate that the gas-film coefficient is independent of liquor rate. The authors used the graphical intercept method and fitted a best line to the $1/K_Ga$ vs. $1/G^{0.8}$. The 0.8 power function arises from the Chilton-Colburn analogy to heat transfer (9). The 0.95 power function of k_La variation with L was obtained by making a best fit of the plot of Hk_La vs. L. Hk_La values were obtained from the expression $1/Hk_La = 1/K_Ga - 30/G^{0.8}$.

ac Yellinger's NH_3 - H_2O absorption work was extensive and quite consistent. The packing materials used included 3/8- to 2-inch Raschig rings, 1/2- to 1 1/2-inch Berl saddles and both stacked and dumped 3-inch spiral tile. Unfortunately this work has never been published.

ad Dwyer and Dodge found no effect between presaturation of tower gas and no saturation. They found a slight decrease in K_Ga with rising temperature. They computed the individual gas film resistance by subtracting the liquid film coefficient of Sherwood and Halloway (20) from the over-all coefficient. They report the following correlations:

0.5-inch rings $\quad 1/K_Ga = \dfrac{1}{0.0065\, G^{0.90}\, L^{0.39}} + \dfrac{1}{0.31\, HL^{0.65}}$

1-inch rings $\quad 1/K_Ga = \dfrac{1}{0.036\, G^{0.77}\, L^{0.20}} + \dfrac{1}{0.103\, HL^{0.78}}$

1.5-inch rings $\quad 1/K_Ga = \dfrac{1}{0.0142\, G^{0.72}\, L^{0.38}} + \dfrac{1}{0.093\, HL^{0.78}}$

ae Hutchings, et al., employed the graphical intercept method, plotting $1/K_Ga$ vs. $1/G^{0.8}$. The 0.8 power term arises from that suggested by the Chilton-Colburn heat transfer analogy (9). The $\left(\frac{X'^m}{G}\right)$ factor is a gas velocity correcting term. It was introduced by Brownell and Katz (43) and is to correct for the effects of packing porosity and type of packing.

af The primary objective of this study is the study of contribution of gas-film diffusivity on the coefficient. Ethanol was chosen because of its marked difference to O_2 and NH_3. The authors conclude that k_La is independent of packing height but that $k_Ga \propto h^{-1/3}$. Their results indicate that the power function of G ($k_Ga \propto G^{0.6-0.8}$) increases as G increases because of progressively better distribution and increased active interfacial area due to greater kinetic energy transfer at higher gas rates. They found no effect of concentration on the coefficients.

Notes for Table II (cont.)

ag The primary objective of this work was the investigation of effect of diffusivity on the gas-film coefficient. The range of diffusivities of the materials studied was two-fold. They correlated their results as $k_G a \propto D_G^{2/3}$ up to G = 600 and L = 3000. Above these rates the results were inconclusive.

ah Doherty and Johnson used the same tower as Borden and Squires (27). They investigated $K_G a$ values for ammonia absorbed in dilute H_2SO_4 and found that the values increased with increasing acid strength, rising to a constant value at normalities greater than 3. This result agrees with the prediction made by the theory of Hatta (31) and (3). They found the acid system gas-film coefficients were 1.45 - 1.65 times those for water. Also, the $K_G a$ values were practically independent of liquor rate over the range 1,200-8,600 lb./hr.ft.^{2}. This is not true in the NH_3-H_2O system.

ai Riggle and Tepe (32) report some thesis data of J. E. Vivian which had not previously been published concerning a series of absorption runs for Cl_2 in dilute NaOH. These runs were made at high chlorine concentrations in the gas so that $K_G a \cdot p_{BM}$ values were computed. Vivian used the formula

$$K_G a \cdot p_{BM} = \frac{G(42p_1 + 29\pi)}{h(\pi - p_1)^{0.8}} \int_{p_1}^{p_2} \frac{dp}{(42p + 29\pi)^{0.8}(\pi - p)^{1.2}\Delta p}$$

This equation assumes $K_G a$ to vary as $G^{0.8}$. Actually the $K_G a$ vs. G plot gave a slope of 0.7. $K_G a$ was found to vary as $L^{1/3}$.

aj Van Krevelen and Hoftizer correlated a large mass of data on the absorption of CO_2 in NaOH and Na_2CO_3 solutions. They suggest that "chemical" diffusion differs from physical diffusion by a factor

$$\frac{x_L\sqrt{\frac{k_I}{D_L}}}{\tanh x_L\sqrt{\frac{k_I}{D_L}}}$$

They arrived at the correlations

$$\frac{k_G d}{D_L} = 0.2\,(G/a_d\mu)^{0.8}\,(\mu/\rho D_L)^{1/3}$$

$$k_L(\mu^2/g\rho^2)/D_L = 0.015\,(L/a_d\mu)^{2/3}(\mu/\rho D_L)^{1/3}$$

They follow the European practice of allowing separately for the effective wetted area of the tower packing. Although this system has been included under the heading "Absorption with rapid, irreversible reaction at liquid interface" evidence indicates that this is neither an accurate nor an adequate classification.

Adams (50) absorbed SO_2 into water in an 18-inch I.D. tile pipe packed with 3-inch spiral tile. The gas was from a commercial sulfur burner. Film resistances rather than coefficients were employed and the individual resistances separated by means of the graphical intercept method of Wilson (6), plotting R_L vs. $1/G^{0.8}$. The range of gas rates was 60-138 lb./hr.ft.^{2} and liquor rates of 150-3480 lb./hr.ft.^{2}. The temperature range was 38-127°F. They found substantial resistances offered by both films, the major one being the liquid film. The over-all liquid resistance varied as the 0.89 power of the liquor velocity.

Johnstone (49) [cited in (7)] absorbed sulfur dioxide from flue gas in a 42-inch I.D. tower packed with 3-inch spiral tile. The absorption took place under such conditions as to oxidize the sulfur dioxide. Johnstone and Singh (10) absorbed sulfur dioxide from gases of 0.2-0.3% (volume) in a rectangular tower containing various types of channels, grids, and packing. The absorbent used was dilute ammonia or caustic soda.

Jenness and Caulfield (51) absorbed sulfur dioxide from sulfur dioxide-air mixtures into water in a 6-inch I.D. tower packed to a depth of 19 inches with 1-inch Raschig rings. They found the liquid film to be the controlling one above liquor velocities of 1510 lb./hr.ft.^{2}. Below this rate the gas film became controlling. The concentration of the feed gas was 10-18%.

Reiley (52) absorbed SO_2 into water in a 20-inch tower packed with wood lattice grids. He used gas from an industrial burner supplying a sulfite mill and varied in concentration from 13-16% SO_2. The water temperature used was near 32° C. He expressed his phase flow rates in terms of linear velocity and insufficient information is given to allow conversion to mass flow rates. He found the system to be one of liquid film controlling.

The most extensive and consistent data thus far are those of Whitney and Vivian (7). They absorbed sulfur dioxide from sulfur burner gases in an 8-inch I.D. lead tower packed to a depth of 24 inches with 1-inch ceramic Raschig rings. They made runs at temperature levels of 50, 60, 70, and 90°F. employing gas rates from 65-851 lb./hr.ft.^{2} and water rates of 920-11,700 lb./hr.ft.^{2}. The concentration of sulfur dioxide in the feed gas varied from 6-17.6%. They resolved the over-all liquid film coefficients into the individual film coefficients at 70°F. by means of the graphical intercept method and arrived at individual film coefficient correlations as follows:

$$\frac{k}{L}a = 0.044L^{0.82} \qquad (24)$$

$$\frac{k}{G}a = 0.028G^{0.7}L^{0.25} \qquad (25)$$

The variation of the liquid film coefficient with temperature agreed well with that found by Sherwood and Holloway (20). over the temperature

range of 50-90°F. They estimated that at $\underline{L}$ = 950 and $\underline{G}$ = 600 lb./hr.ft.^{2}, 90% of the over-all resistance resides within the liquid film; at $\underline{L}$ = 11,700 and $\underline{G}$ = 90 the liquid film contributes 40% of the over-all resistance.

Pearson, Lundberg, West, and McCarthy (53) absorbed sulfur dioxide into water from an air-sulfur dioxide in a 12-inch I.D. tower packed with 1-inch Raschig rings. They used a packed height of 19.45 feet, a height approaching that of a commercial tower. The gas flow rates were 148-335 lb./hr.ft.^{2} and liquor rates of 4930-7490 lb./hr.ft.^{2}. The concentration of sulfur dioxide in the feed gas was in the range 5.4-19%. The temperatures used were in the range of 17 to 32°C.

Pearson, et al., computed their data in terms of the pseudo-coefficient (to be explained in Part E of this section), using solubility data correlated by means of the correction for ionic strength suggested by Johnstone and Leppla (54). They report their data as showing good agreement with those of Whitney and Vivian (7).

A study of the literature cited in the preceding pages indicates that, except for the work of Johnstone (49), all of the work done in the field of sulfur dioxide absorption has been for the case of gases containing relatively high concentrations (10-20%) of solute. Although Johnstone and Singh (10) investigated the region of low gas concentration

their objective was the removal of sulfur dioxide by means of oxidation. For this reason they employed various lattice and grid packings and suitable catalysts. Their oxidation method was so efficient that the rate of absorption of oxygen became the controlling rate, but their data afford no means of comparison with sulfur dioxide absorption at higher concentrations carried out in a packed tower.

E. THE EQUILIBRIUM SOLUBILITY OF SULFUR DIOXIDE IN WATER AND SULFURIC ACID

The situation as regards the literature on the equilibrium solubility of sulfur dioxide in water parallels that of absorption. Quite a large amount of solubility data are reported for the higher concentrations. Plummer (74) has recently compiled and correlated all available data on the solubility of sulfur dioxide in water. But there are practically no low-concentration data in the literature. Morgan and Maass (75) report a few as also do Johnstone and Leppla (54). There have been no data published for the temperatures 50, 70, and 90°F.

Johnstone and Leppla also report a few data for the solubility of sulfur dioxide of low concentration in dilute sulfuric acid. They used acid strengths of 0.0879, 0.5174, and 1.103 molal and a temperature of 25°C.

F. THE PSEUDOCOEFFICIENT OF VIVIAN AND WHITNEY

According to the conditions stated by the two-film theory (page 4) for those cases in which absorption is accompanied by chemical reaction, the rate of reaction must be very much greater than the rate of diffusion of the solute into the liquid. The driving forces are obtained from the equilibrium relationship between partial pressure and total concentration of dissolved solute. Vivian and Whitney (17) suggest that the two-film theory may also be applied to those cases of chemical absorption in which the rate of reaction is vanishingly small as compared to the rate of diffusion. In these cases the solute travels through the liquid film un-reacted, the reaction occurring within the main body of the liquid phase.

The driving force is different for this case since it is based on the molecular or un-reacted solute concentration, and this results in a different value for the absorption coefficient called the pseudo-coefficient in order to distinguish it from the normal coefficient computed in the usual manner. How the absorption driving force for the pseudocoefficient differs from that of the normal is shown in Figure 4. The primed letters refer to the pseudocoefficient terms.

Line OA is the equilibrium curve based on total solute concentration and OB the equilibrium curve based on molecular or un-reacted

concentration. The operating lines are also based on the total (normal) or molecular (pseudo-) concentrations and in Figure 4 are $\underline{c}_1\underline{c}_2$ and $\underline{c}'_1\underline{c}'_2$. The driving force is then equal to either $(\underline{c}_e - \underline{c})$ for the normal or $(\underline{c}'_e - \underline{c}')$ for the pseudo case. Equation (13) may then be rewritten as

$$(\underline{K}_L\underline{a})_n = \underline{L}/\underline{h}\rho\int_{\underline{c}_1}^{\underline{c}_2} d\underline{c}/(\underline{c}_e - \underline{c}) \qquad (26)$$

for the normal over-all coefficient and

$$(\underline{K}_L\underline{a})_{\underline{p}} = \underline{L}/\underline{h}\rho\int_{\underline{c}_1}^{\underline{c}_2} d\underline{c}/(\underline{c}'_e - \underline{c}') \qquad (27)$$

for the pseudocoefficient. Attention is called to the fact that the amount of sulfur dioxide transferred $[L/\rho\ (\underline{c}_1 - \underline{c}_2)]$ is the same for both calculations.

Examination of the pseudocoefficient reveals that (1) the pseudocoefficient is always larger than the normal coefficient and (2) the two coefficients approach each other as the two equilibrium lines approach each other. The limit is for the two equilibrium lines to become identical, in which case the pseudo- and normal coefficients become equal and the system behaves as though the absorption were a purely physical one.

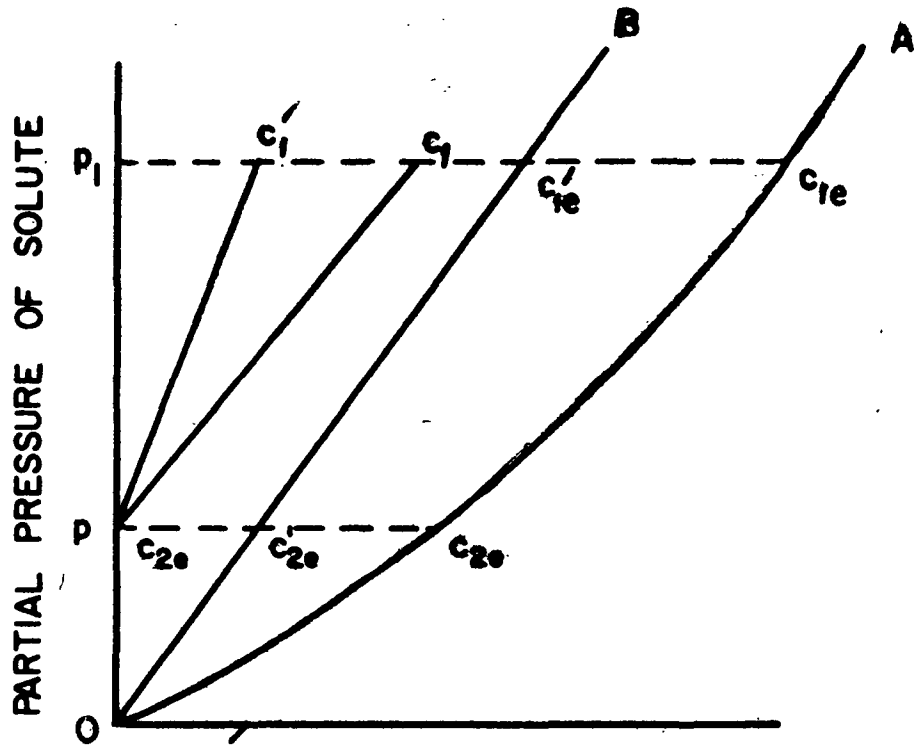


Figure 4. Operating Diagram Illustrating the Difference in Driving Forces for the Pseudo – and Normal Absorption Coefficients.

For systems which undergo reversible reaction with water (such as chlorine or sulfur dioxide) suppression of hydrolysis should cause the two coefficients to approach each other. In fact, Vivian and Whitney report the results of preliminary experiments on the absorption of chlorine into 0.1 N HCl* which gave absorption coefficients agreeing closely with those predicted from oxygen desorption data.

*For this strength acid suppression is sufficient to permit hydrolysis of only about 1% of the dissolved chlorine.

IV. STATEMENT OF THE THESIS PROBLEM

In a typical case of absorption of sulfur dioxide in the pulping industry, absorption is made into a solution containing 0.5-2.0% base. From the sulfite-free base to the gas-saturated solution a series of chemical transformations occur which may be chronicled as:

1. Production of normal sulfite

$$2BOH + SO_2 + H_2O \rightarrow B_2SO_3 + H_2O$$

2. Production of bisulfite

$$B_2SO_3 + SO_2 + H_2O \rightarrow 2BHSO_3$$

3. Saturation of solution with excess of sulfur dioxide

$$BHSO_3 + SO_2 + H_2O \rightarrow BHSO_3 + H_2SO_3$$

If the absorption is considered to be carried out in a conventional packed tower operating with gas and liquid phases flowing counter-current to each other, then the tower may be pictured as comprising three regions which correspond to each of the enumerated reactions.

The first step is presumably the formation of sulfurous acid which reacts with unreacted base to form the normal sulfite; the second converts the sulfite to the bisulfite. When all the base

present has reached to form bisulfite, the sulfur dioxide then forms an excess of dissolved sulfur dioxide. This third step takes on added importance when it is considered that from two to six times as much sulfur dioxide will normally be absorbed in this region as in either of the other two. At once questions arise concerning the various absorption rate-determining factors involved in the transfer of sulfur dioxide from the gas to the liquid phase and how these rates are affected by the variables encountered in absorption practice.

The present work has a three-fold purpose: (1) The investigation of the equilibrium solubility of sulfur dioxide at low concentration (below 1.5%) in water and water containing a common ion for the suppression of the hydrolysis of sulfur dioxide (thus simulating the saturation step illustrated by the step-wise equations), (2) the investigation of the rate of absorption for low-concentration sulfur dioxide into water and (3) the investigation of absorption rate into the hydrolysis suppressed system.

V. DESIGN OF EXPERIMENTS AND EXPERIMENTAL PROCEDURES

A. CONSIDERATIONS CONCERNING THE THESIS APPROACH

An 8-inch I.D. tower packed with 1-inch Raschig rings was chosen as the absorption equipment in order that the data resulting from the experiments may have utility for the design of large-scale towers (48). In order to achieve the objectives outlined in SECTION IV above it is necessary to make absorption studies on four systems: (1) High concentration sulfur dioxide-water, (2) oxygen desorption from water, (3) low-concentration sulfur dioxide-water, and (4) low-concentration sulfur dioxide-water (hydrolysis suppressed).

The procedures and techniques involved in determining high-concentration sulfur dioxide-water absorption data and oxygen desorption data have been worked out and discussed elsewhere, so only the details of the experimental procedures will be given (7,20).

Any attempt to study the absorption of low-concentration sulfur dioxide gas encounters difficulties due to the oxygen susceptibility of the system and the analytical problems involved. A number of considerations thus dictate the design of and conditions for the experimental procedures. These considerations may be summarized briefly as follows:

(1). Gas concentration levels were established as 0.75% (volume) for water and 1.50% for the suppressed system.

(2). Hydrolysis suppression of sulfur dioxide was by means of sulfuric acid. It was originally planned to employ sodium and ammonium bisulfites but oxidation and analytical difficulties forced abandonment of this plan. The concentration of suppressant was determined as that amount causing an increase of only 1% in the relative viscosity of water at 70°F.

(3). The height of tower packing is controlled by considerations of driving force determination for absorption runs. Two feet of packing was adopted for the high-concentration sulfur dioxide-water runs and one foot for the low-concentration. Both one and two feet were used for the oxygen desorption runs.

(4). The tower end effect is of great importance as a correcting term and an estimation of this effect was therefore necessary.

(5). The analytical problems presented difficulties for both the gas and liquid phases. Solutions of these problems are presented and discussed in detail in APPENDIXES III and IV.

(6). Solubility data for the sulfur dioxide-water and dilute acid systems were determined for the region of low gas concentration employed.

B. DETERMINATION OF LIQUOR PROPERTIES: DENSITY AND VISCOSITY

1. SUMMARY OF DETERMINATIONS

The densities and relative viscosities of sulfuric acid, sodium bisulfite, and ammonium bisulfite solutions were determined at 70°F. to a strength as high as 0.500 molal.

The densities of low-concentration solutions of sulfur dioxide in water and 0.0580 molal sulfuric acid were determined over the temperature range 50-100°F. The concentration of sulfur dioxide dissolved in the solutions ranged, in milliequivalents per gram of solution, from 0-0.11 for water and 0-0.09 for sulfuric acid.

2. CHEMICAL PURITY OF REAGENTS USED

Triple-distilled water was used for making up solutions for studies of physical properties. The service-distilled water was redistilled from alkaline permanganate and this distillate redistilled from phosphoric acid. The water was then deaerated to an oxygen content of less than 0.5 parts per million.

The sulfur dioxide used was refrigerant grade furnished in 25-lb. cylinders. The other chemical reagents—sulfuric acid and sodium and ammonium hydroxides—were of reagent quality. Nitrogen was of the water-pumped grade.

3. PREPARATION OF SOLUTIONS

The sulfuric acid solutions were prepared by weighing the proper quantity of acid of known strength and adding it to a weighed quantity of pure water. Five hundred milliliter quantities of bisulfite solution were prepared in an all-glass reaction flask by introducing a weighed quantity of sodium or ammonium hydroxide solution of proper strength and then pure, dry sulfur dioxide. The introduction of sulfur dioxide was discontinued when the correct weight had been added. This method allowed accurate control of reactant concentration since weighings could be made to 0.005 grams. Preparing solutions in this manner avoided the complications of handling and possible atmospheric oxidation. The weight of sulfur dioxide gas above the solution was small enough to be neglected.

The solutions containing excess sulfur dioxide were made in the same manner as that described above for preparing bisulfites.

4. THE DETERMINATION OF LIQUOR DENSITY

Liquor density determinations were made by means of a pycnometer. The pycnometer used was of 29-ml. capacity with the usual ground joint and capped capillary. The solution and pycnometer were brought to constant temperature by immersion in the thermostat. The pycnometer was quickly filled and drained once, filled again, closed, and weighed.

Some difficulty was experienced with moisture condensation on the outside surface of the pycnometer when solutions of low temperature were handled. This difficulty was minimized by adjusting the room temperature to a level at or below the temperature of interest.

5. THE DETERMINATION OF VISCOSITY

Relative viscosity determinations were made at 70°F. in Ostwald viscometers having efflux times for water between 260-310 seconds. The viscometers were clamped into a cylindrical battery jar, the jar being small enough to allow the entire assembly to be immersed in the thermostat. The viscometer was charged with solution and allowed to come to the controlled temperature; the jar and contents were then lifted out and placed on a table for convenience in making the viscosity run. The reservoir of water in the battery jar served to keep the temperature constant during the run. The viscometer was recharged with fresh solution for each run and the whole assembly reimmersed in the thermostat.

Relative viscosity was computed by means of the expression $\eta = \underline{d}_1\underline{t}_1/\underline{d}_2\underline{t}_2$ where η = relative viscosity (compared to water); $\underline{d}$ = density, grams/ml.; and $\underline{t}$ = efflux time, in seconds. Subscripts 1 and 2 refer to solution and water respectively.

C. DETERMINATION OF EQUILIBRIUM SOLUBILITY OF SULFUR DIOXIDE IN WATER AND IN 0.058 MOLAL SULFURIC ACID AT LOW GAS CONCENTRATION

1. SUMMARY OF DETERMINATIONS

Sulfur dioxide solubility determinations were made over a partial pressure range of 0-0.04 atmospheres and between temperatures of 50 and 90°F. Forty-two runs were made with the water system and 27 runs with 0.0580 molal sulfuric acid. Six comparison runs were made on bisulfite solutions—3 on 0.0580 molal sodium bisulfite and 3 on 0.0580 molal ammonium bisulfite solution at 70°F.

2. DESCRIPTION OF THE METHOD AND APPARATUS USED

The determination of equilibrium solubility of sulfur dioxide employs a dynamic method in which the gas is bubbled through the liquor. The equilibrium solubility of gas was determined as a function of gas solute partial pressure for different levels of temperature. This method requires a source of gas of constant composition, a suitable solubility, a constant temperature bath, and cell train auxiliaries for gas humidification and for sealing the system from the atmosphere.

The cell employed is shown in cross section in Figure 5. Forty milliliters of liquor comprised a cell charge. The charge was introduced into the cell by forcing it from a reservoir with nitrogen. After charging, the cells were arranged in the constant temperature thermostat, supported under a support plate by engaging lugs into holes drilled into the cell cover.

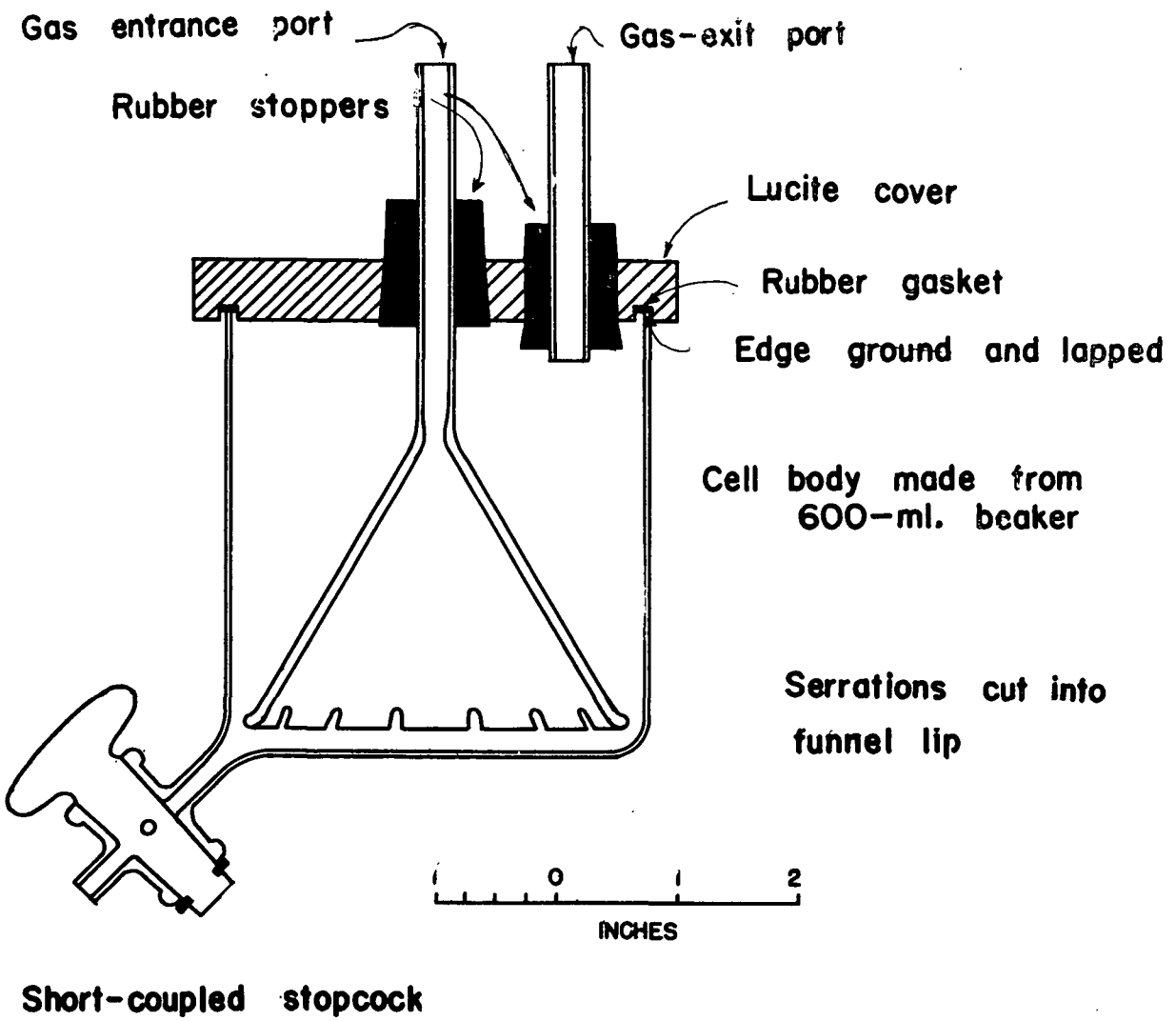


FIGURE 5. Gas-Liquor Equilibrium Solubility Cell.

Three cell trains were constructed to allow three determinations to be made at a time. Each train consisted of (1) a tank of prepared gas [sulfur dioxide-nitrogen] of the desired solute concentration, (2) a 4-inch humidifying column of glass rings in a tube containing pure water through which the gas bubbled, (3) a conditioning cell, (4) the equilibrium-solubility cell, and (5) a low-head trap to seal the system from the atmosphere. A schematic diagram of the cell train is shown in Figure 6. The conditioning cell is identical with the equilibrium-solubility cell and functioned to adjust the humidity of the gas flowing into the equilibrium cell.

The cell train, exclusive of the gas tank, was immersed in a water-filled thermostat provided with a low-head re-circulating pump to provide a vigorous flow of water through the tank. Temperature control of the bath followed the principle of adding a sufficient excess of cold water to compensate for the heat gained from pump work and the surroundings and trimming this excess with electrical heaters operated by a temperature regulator and relay. Heat was supplied by means of three bayonet heaters of 625-watts total capacity operated by a Precision Merc-to-Merc regulator and relay. The heaters were located at the discharge outlet and were turned slightly to the stream in order to assure good mixing. A deflecting vane located beyond the heaters deflected the flow of water downward to help create turbulence in the tank.

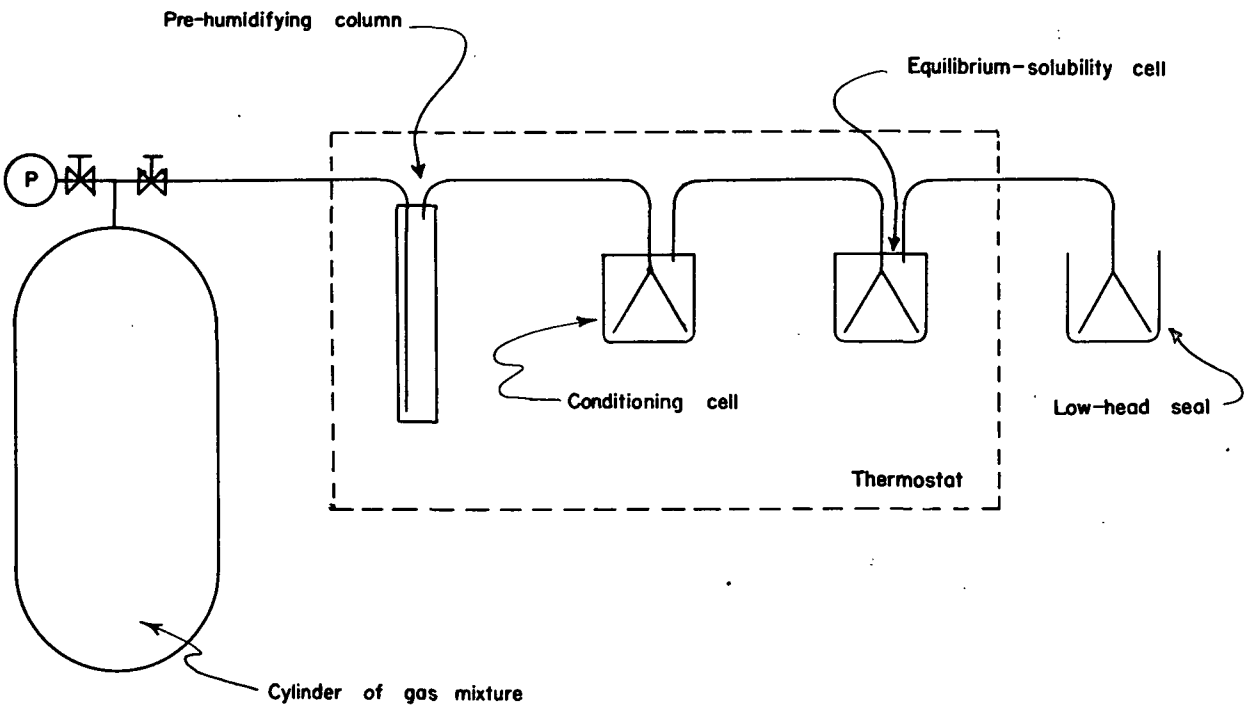


FIGURE 6. Equilibrium-Solubility Cell Train.

Temperature regulation proved to be uniform and constant to within ±0.04°F.

Gas mixtures were prepared in 2100-cubic inch war-surplus breathing oxygen tanks by introducing sulfur dioxide and nitrogen in the proper amounts. The tanks were fitted with internal vanes which could pivot on a central shaft when the tank was tumbled and thus assured uniform gas mixtures. Gas mixtures had a usual pressure of 130 pounds per square inch absolute, corresponding to about 11 cubic feet of gas at standard conditions. The gas was throttled from each tank to the cell train by means of a needle valve.

Difficulties encountered during the first runs indicated the desirability of charging the cell initially with liquor having approximately the final equilibrium strength. This was done by introducing into the cells aliquots of two solutions—one containing no dissolved gas and the other a sufficient amount of gas to give approximately the desired final concentration. The solutions were measured from graduated gas burets modified to enable the handling of liquor. It was also found desirable to disengage the cells from time to time and shake them in order to assure proper mixing of the contents.

The gas was allowed to pass through the cell for an hour, a sample drawn and analyzed and another sample drawn at the end of an additional half hour. If the analyses for the two samples agreed within 1% the run was discontinued. If the two failed to agree, the run was continued if sufficient gas and liquor remained. Usually a failure to obtain agreement within two such runs required that the entire run be made again.

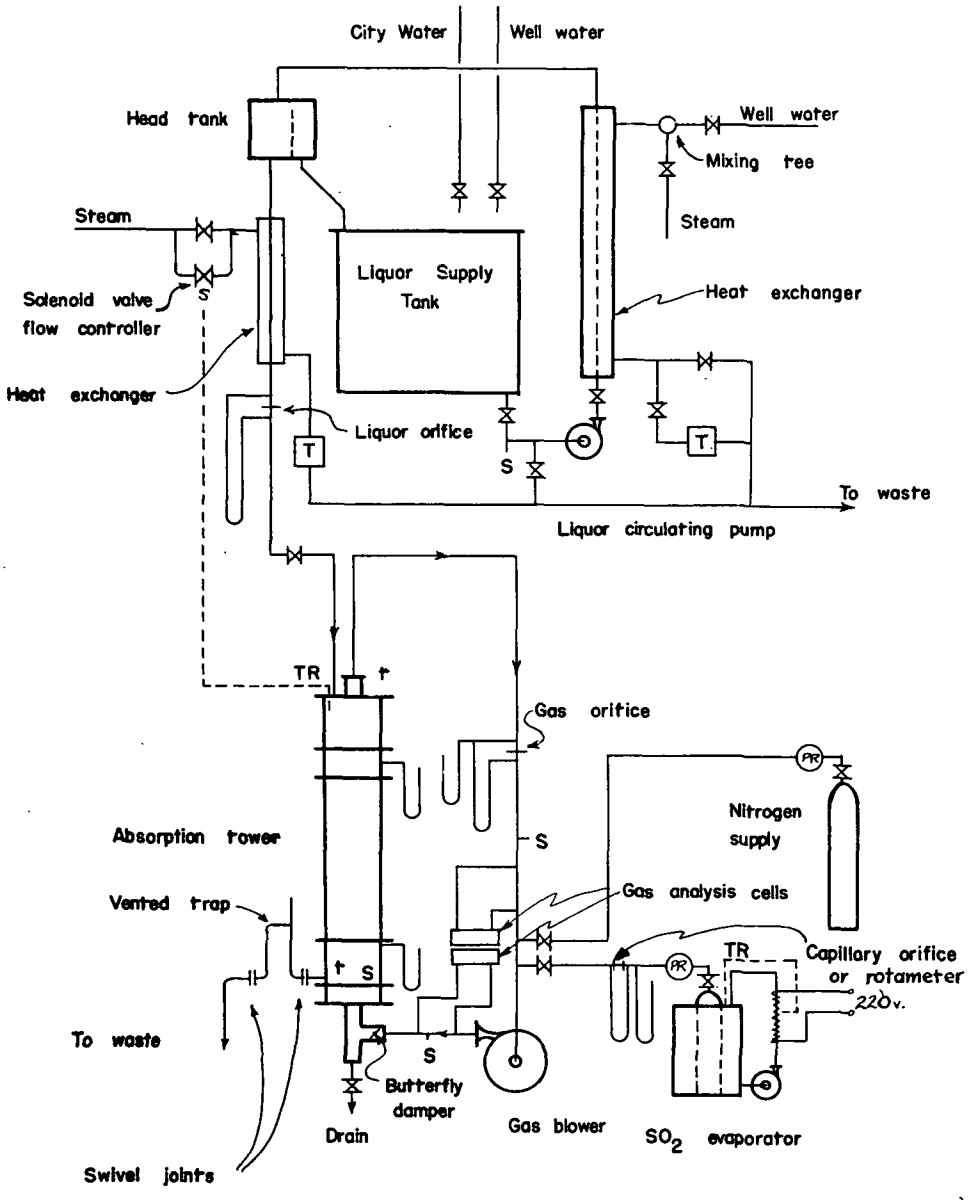
D. THE DESORPTION OF OXYGEN FROM WATER

1. SUMMARY OF RUNS

Oxygen desorption runs were made at one, two, and three feet of packed height and under conditions of (1) constant liquor rate-variable gas flow rate and (2) constant gas flow rate-variable liquor flow rate. Temperatures employed were 70, 80, and 90°F. of 126 runs made only 64 are reported. Those runs made at 90°F. were discarded because of saturation difficulties as also were all those made at three feet of packed height because of the close approach of the liquor concentration to the equilibrium values.

2. EXPERIMENTAL EQUIPMENT

A schematic diagram of the absorption tower system used is shown in Figure 7 and a photograph of the equipment is shown in Figure 8. A complete, detailed description of the tower and its



t Point of temperature measurement
S Point of sampling
T Trap
PR Pressure regulator
R Relay
TR Temperature regulator

FIGURE 7. Schematic Diagram of Absorption Tower and Tower Auxiliaries

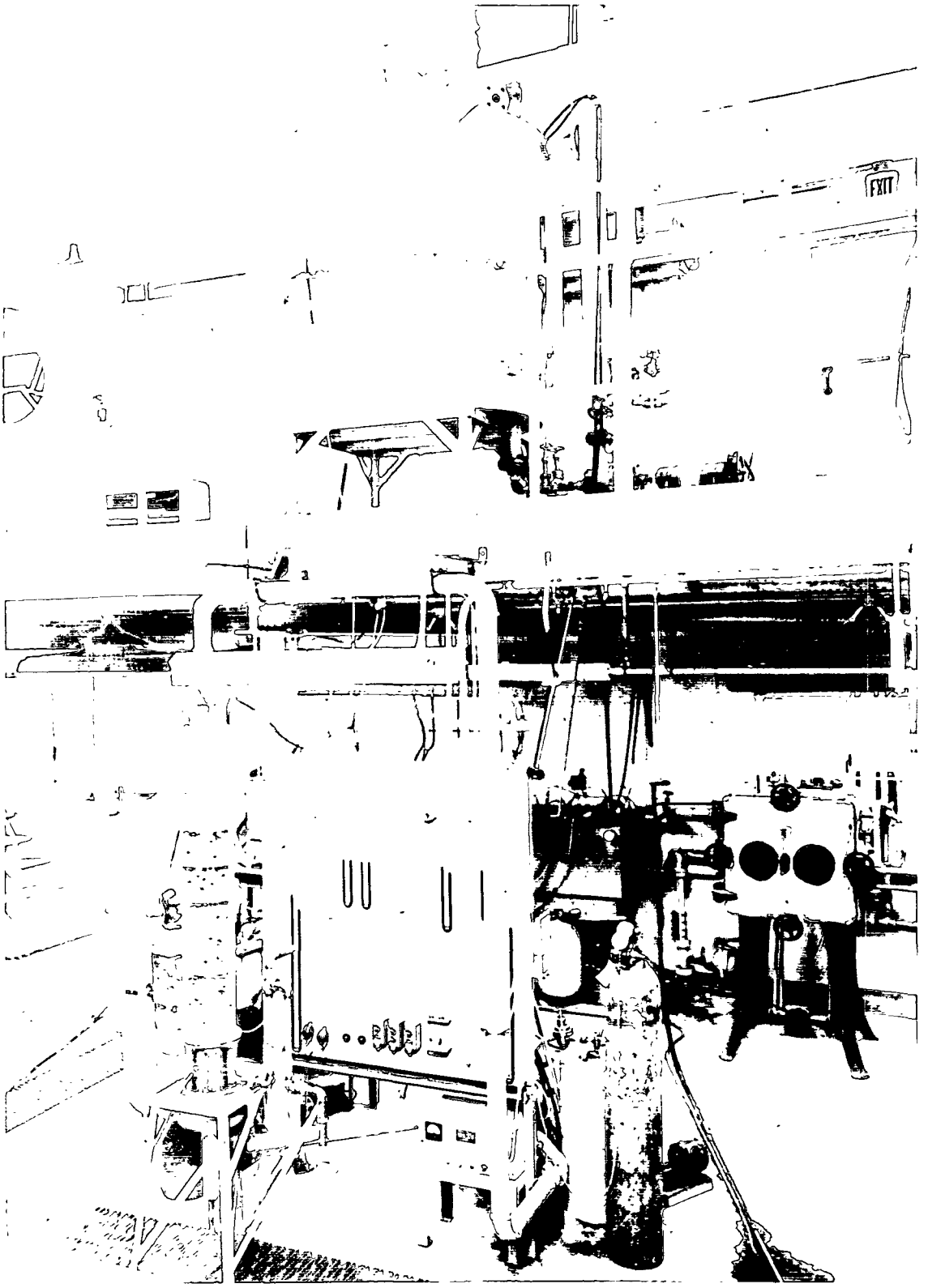


FIGURE 8 Arrangement of Absorption Tower and Tower Auxiliaries.

auxiliaries is given in APPENDIX II. Certain modifications were necessary for the oxygen desorption studies.

The design of the tower system embodies the recycle of gas and thus eliminates the need for a saturator. A closed cycle for oxygen desorption is not possible, however, because of the disturbance of the oxygen content of the gas in the time necessary to establish steady-state conditions (3-7 minutes). Two methods were used for saturating the feed air: (1) injection of steam, and (2) saturation in a packed tower.

The use of steam for saturation involved breaking the gas run just ahead of the blower suction so that air was drawn directly from the room. The exit air from the tower was discharged from the end of the gas run beyond the gas orifice. The temperature of the air in the room was brought to a level of about 20°F. below that desired in the tower. Steam was then injected into the air at the blower suction until the desired air temperature was attained.

Runs 290-308 involved the use of compressed air from the service supply which had been saturated in a separate packed tower saturator. The saturated and tempered air was brought to the gas blower through a 1-inch industrial hose. This limited the amount of air at about 65 $lb./hr.ft.^2$.

Oxygen was introduced into the liquor recycle line at a point just beyond the pump throttle. By introducing the gas at this point, the oxygen feed entered the water under a hydraulic head of approximately 8 feet, moving along with the water for a length of about 10 feet of pipe to allow mixing and solution, and the water discharged into the liquor head tank where any trapped gas could flash off. A gas bubbler on the oxygen feed was employed as a visual guide for adjustment of the rate of oxygen addition.

Appleton city water, without further treatment, was used.

In a typical run the packed height of the tower was adjusted by bolting together the desired length of section and filling with dumped rings to the desired height. The temperature and flow rates for gas and liquor were adjusted at the desired levels and the tower allowed to run a minimum of 7 minutes in order to establish steady-state conditions. Two liquor samples were then drawn corresponding to the feed and exit liquors. The samples were drawn into 250-ml. ground glass stoppered bottles with care being taken to avoid disturbing the sample. Details of the liquor analysis for the oxygen runs is given in Part D of APPENDIX III.

Liquor flow rates were determined by weighing the outflow into a tared pail; gas rates were determined by orifice metering. All runs were made with the liquor pool level adjusted at 1.5 inches below the top surface of the gas upcomer caps.

E. ABSORPTION OF SULFUR DIOXIDE FROM GASES OF HIGH-SOLUTE CONCENTRATION

1. SUMMARY OF RUNS

A total of 15 runs (55-69) were made in which sulfur dioxide was absorbed into water from gases at 5% or more solute. All runs were made at 70°F. with two feet of tower packing. Three levels of liquor rate were maintained: 950, 2270, and 4900 lb./hr.ft.^{2}. At each liquor rate level, five gas rates were used which ranged between 87 and 942 lb./hr.ft.^{2}.

2. EXPERIMENTAL PROCEDURES

The absorption was carried out in a closed cycle system as is described in detail in APPENDIX II. Only one modification was made and that was the substitution of a No. 5 Stabl-Vis rotameter for the smaller one normally used with the tower.

The gas side of the tower was operated as a closed cycle of nitrogen into which sulfur dioxide was introduced in sufficient quantity to produce tower feed gas at approximately the desired concentration level. Rates of sulfur dioxide input required for each run were estimated on the basis of existing sulfur dioxide absorption data. The large rotameter was calibrated in order to serve as a means of establishing the approximate level of gas

concentration. For any run the temperature and phase flow rates were set and the gas introduced at the estimated rate. After analyses were made on the first series of runs, corrections were applied for the second series and then for the third. Liquor flow rates were determined by weighing the outflow and the gas rates by means of orifice metering. Gas and liquor samples were drawn for analysis after 10 minutes of tower operation.

The liquor was analyzed as 23-ml. samples drawn from a sampling pipet into evacuated 200-ml. balloons. The liquor analysis procedure is given in APPENDIX III. Gas samples were drawn into 1-liter gas-weighing balloons and analyzed according to the method of APPENDIX III.

F. ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW-SOLUTE CONCENTRATION

1. SUMMARY OF RUNS

The principal work of this thesis resides in the absorption tower runs involving the absorption of sulfur dioxide from gases of low concentration into either of two solutions--pure water or 0.0580 molal sulfuric acid. Runs were made over a range of temperatures of 50-90°F., packed height of one foot (15 runs were made at two feet of packed height), a range of gas flow rates of 90-680 lb./hr.ft.^{2} and of liquor flow rates of 900-11,000 lb./hr.ft.^{2}. Most of the runs were made at 70°F.

2. EXPERIMENTAL PROCEDURE

It was originally planned to employ a packed height of two feet throughout the thesis work, but trials indicated that this height caused an excessive amount of the solute to be removed at the higher gas rates. The original plan of using feed gas of 0.75% sulfur dioxide also had to be modified for the case of sulfuric acid to a top limit of approximately 1.50%. The higher value became necessary in order to assure a sufficient amount of absorption to obtain accuracy in the analysis of the exit liquor.

The absorption runs were carried out in a closed gas cycle (see APPENDIX II). Appleton water was used, which had first been tempered and deoxygenated. Tempering was accomplished by injecting steam directly into the water (37-45°F) until the desired temperature was reached. The dissolved oxygen was removed by adding a slight excess of sodium sulfite. The sulfite requirement was determined by making a preliminary analysis by the Winkler method (69) (as described in APPENDIX III) and estimating the amount of sulfite needed. After the sulfite addition, a recheck was made to ascertain that all oxygen was in fact removed. For a full tank of water (410 gallons) approximately 120-140 grams of sulfite were required. The sulfite, except for a small residual amount, is converted to sulfate and contributes approximately 800 p.p.m. of sodium to the water.

Investigation proved that the influence of this quantity of sodium sulfate on the solubility of sulfur dioxide in water is so slight as to be negligible. The effect of any excess of sulfite was corrected by means of a blank analysis on the feed liquor.

In the sulfuric acid system studies 0.0580 molal acid was made from deoxygenated and tempered city water by the addition of the required amount (approximately 19 lb.) of Grasselli reagent grade concentrated acid. Concentration accuracy of the diluted acid was maintained to three significant figures. Analysis was made by means of the titration of a sample against standard alkali.

Seven or eight tower runs were usually made in a single series. Before beginning a run, nitrogen was used to purge the tower of oxygen. Approximately 10 cubic feet of gas were used, which corresponds to something like five times the void volume of the tower. During the course of the tower runs a sufficient quantity of nitrogen was bled into the system to exert a back pressure of 0.5 inch and thus seal the system from air.

Although the tower apparatus had provision for automatic temperature control, experience proved that too much time was required for adjusting the controller, thus impairing the operating flexibility. Liquor temperatures were therefore manually controlled by feeding water

to the head tank at 1-3°F. above the desired temperature and then trimming this by running cold water through the concentric heat exchanger on the liquor feed line. The system responded quickly and permitted control, in most cases, to within 0.2°F. of that desired.

Since no separate saturator was employed there was no effective control of feed gas temperature. The gas leaves the tower saturated and tempered, but heat transmission to or from the gas run and heat input due to blower shaft work can cause variance in the feed gas temperature. This difference in temperature was small, however, and was seldom more than 3°F.

The tower equipment proved to be quite flexible and responsive during tower runs. Changes in operating conditions were easily and quickly made and each run was allowed to run a minimum of seven minutes operating time in order to assure steady-state conditions. Tower runs at the lower liquor rates were allowed to run for longer times—frequently 15-20 minutes. Tests show that the steady-state condition was usually reached within about four minutes.

Troubles were encountered in some runs with a drift in the sulfur dioxide feed rate after the control valve was set. This required the attention of an additional operator to make certain that the sulfur dioxide feed remained constant during a run.

Ultraviolet absorption analysis (APPENDIX IV) of the feed gas was used as the means of indicating the proper inlet gas concentration for controlling the rate of feed of sulfur dioxide to the system. The gas analyses for computing absorption coefficients were obtained by iodometric analysis of 1-liter samples of the tower gases according to the method described in APPENDIX III. Liquor samples were drawn from the 23-ml. sampling pipet and analyzed by the method of APPENDIX III.

VI. RESULTS AND DISCUSSION

A. THE PHYSICAL PROPERTIES OF THE ABSORBENTS

Table III presents the results of density and relative viscosity measurements made on three liquors of interest—sulfuric acid and sodium and ammonium bisulfite. These data are plotted in Figures 9 and 10. The density data for the aqueous solutions of these three substances were necessary for the computation of relative viscosity. It is seen in Figure 10 that the relative viscosity of 0.0580 molal sulfuric acid at 70°F. is 1.01. This increase of 1% in viscosity was taken as an arbitrary upper limit for the disturbance of liquid viscosity, which has an important effect on the liquid film properties and the diffusivity of solute through the liquid film. This choice of acid strength was also influenced by considerations of efficiency of hydrolysis suppression, safety, corrosion, and economy. Complete hydrolysis suppression would have required a much stronger solution—as high as 1 or 2 normal. Such high strength would, however, have serious effects on the viscosity and on the other considerations. In the light of results of the absorption experiments 0.0580 molal seems low and probably should have been twice as strong.

Accurate calculations of the concentration of solute in liquor on a volume basis require a knowledge of the concentration-temperature-density relationship for dilute sulfur dioxide solutions. Campbell and

Maass (57) determined a series of sulfur dioxide-water solution density isotherms at solute concentrations above the range of this thesis. These data were interpolated to the density of water (zero concentration) and cross plotted to give the isotherms shown in Figure 11. Values of density over the same low range of concentration determined experimentally using the 29-ml. pycnometer were found to agree with the values of Figure 11 within 0.15%. This good agreement is considered to indicate the reliability of the pycnometer method used for determining the densities of dilute sulfur dioxide-sulfuric acid solutions reported in Table IV and plotted in Figure 12.

TABLE III

DENSITY AND RELATIVE VISCOSITY OF AQUEOUS SOLUTIONS OF SULFURIC ACID, SODIUM BISULFITE, AND AMMONIUM BISULFITE AS A FUNCTION OF CONCENTRATION AT 70°F.

(Figures 9 and 10)

Solute	Molality	Density	Relative Viscosity
Sulfuric acid	0.0800	1.004	1.021
	0.1600	1.008	1.027
	0.2400	1.014	1.037
	0.5000	1.029	-
Sodium bisulfite	0.0851	1.004	1.009
	0.1723	1.010	1.032
	0.3023	1.020	1.060
	0.4010	1.027	1.079
	0.4859	1.033	1.093
Ammonium bisulfite	0.0819	1.002	1.006
	0.1614	1.006	1.012
	0.3250	1.013	1.030
	0.4019	1.017	1.035
	0.5000	1.021	1.048

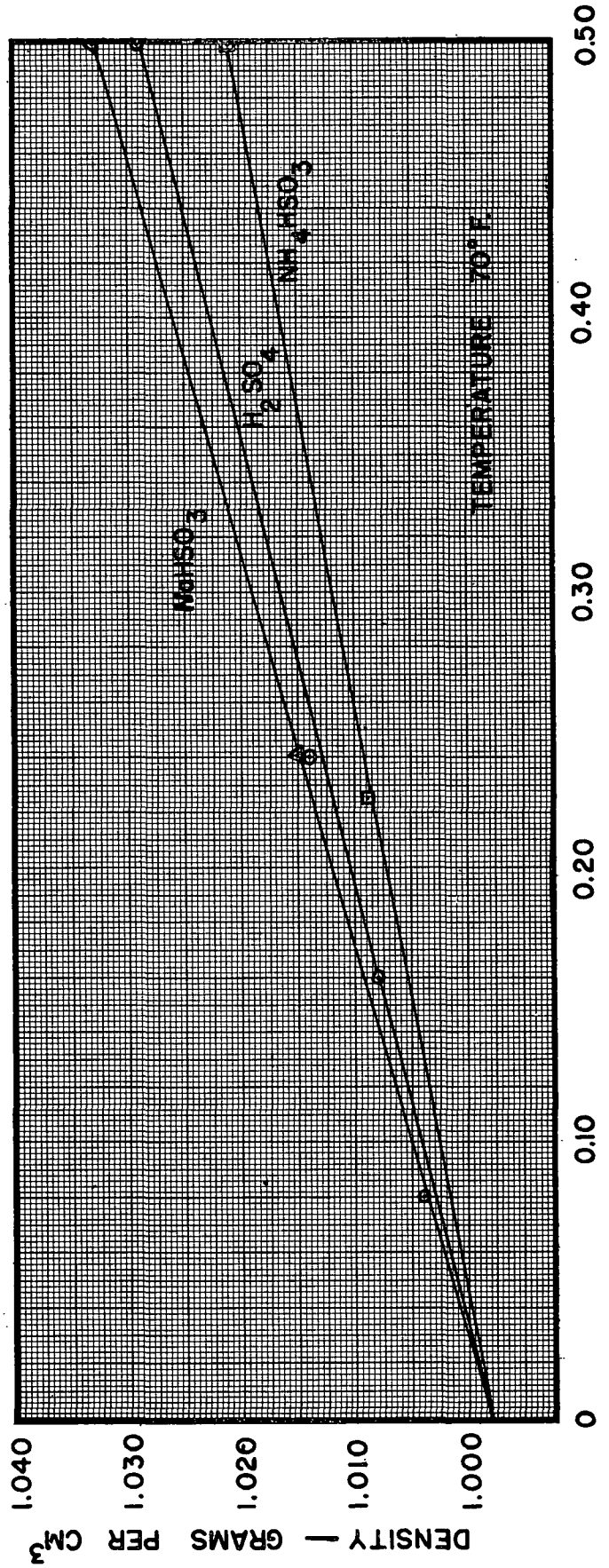


Figure 9. Density of Aqueous Solutions of Sulfuric Acid, Sodium Bisulfite, and Ammonium Bisulfite.

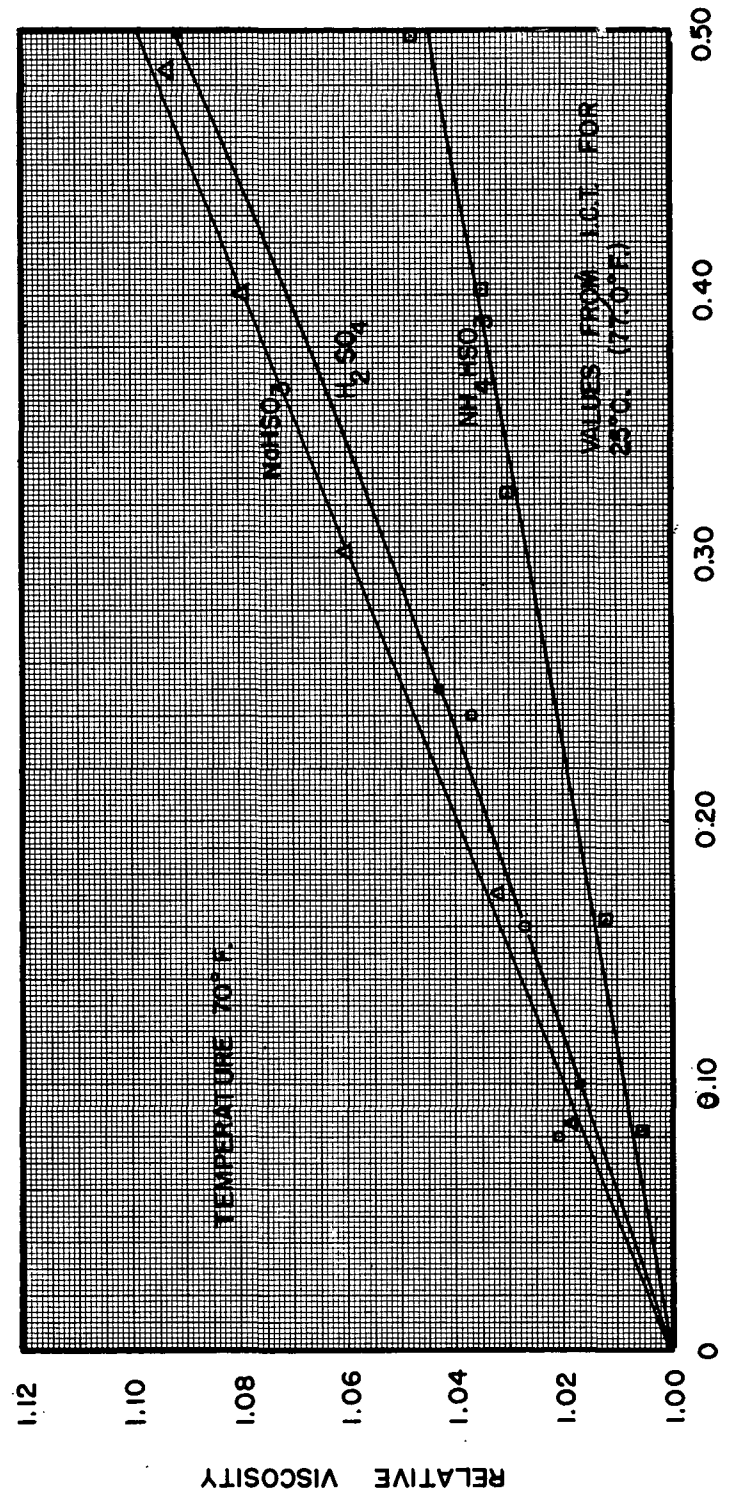


Figure 10. Relative Viscosity of Aqueous Solutions of Sulfuric Acid, Sodium Bisulfite, and Ammonium Bisulfite.

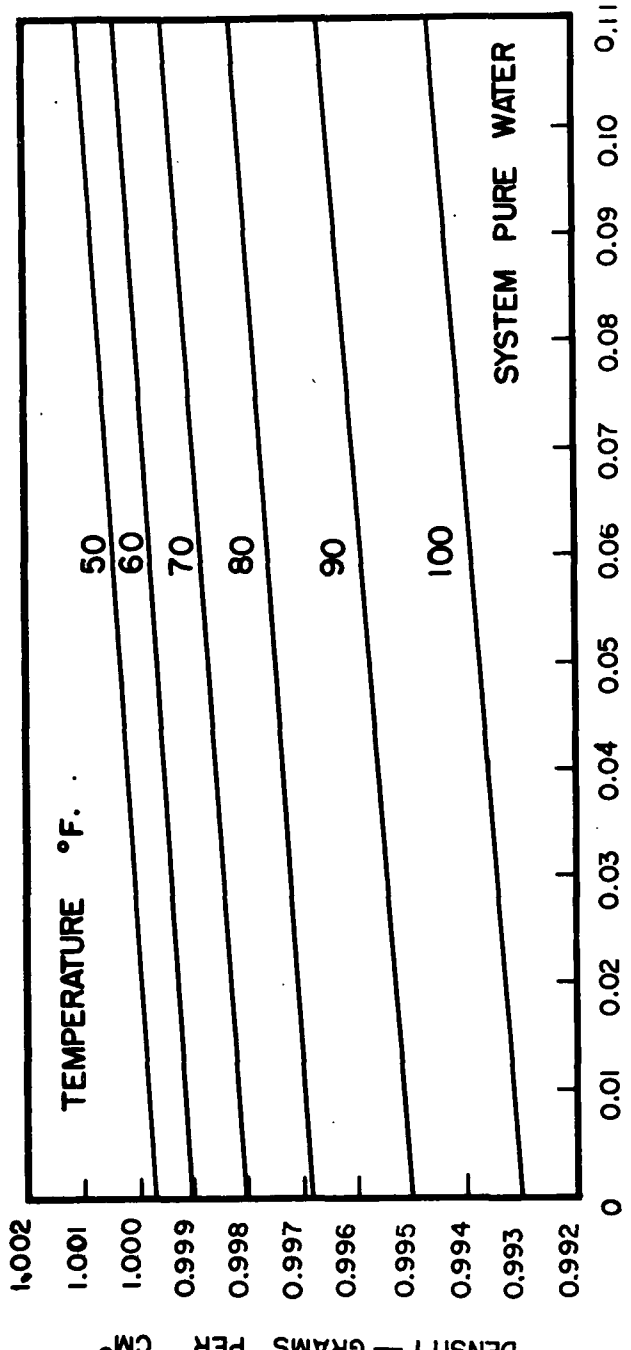


FIGURE 11. Density of Aqueous Solutions of Sulfur Dioxide. From the Data of Campbell and Maass (57).

TABLE IV

DENSITY OF SOLUTIONS OF SULFUR DIOXIDE AT LOW CONCENTRATION IN 0.058 MOLAL AQUEOUS SOLUTIONS OF SULFURIC ACID

(Figure 12)

System	Conc. SO_2, Meq./g.	Density at Temp., °F. 51.1	59.9	70	80	89.2	98.8
Sulfuric acid	0	1.003	1.003	1.002	1.001	0.9997	0.9981
	0.0610	1.004	1.004	1.003	1.002	1.001	1.000

B. SOLUBILITY DATA

Table V presents the complete sulfur dioxide solubility data for this thesis. The data for the solubility of the gas in pure water at 50, 70, and 90°F. between 0 and 0.02 atmospheres partial pressure are shown in Figure 13. In Figure 14 is shown a comparison of data for the higher concentration range with those determined for the low range. The plot shows the upper limit of values for this thesis are in good agreement with the literature and shows the decided curvature of the low-concentration data which differs from the usual interpolation of the high-concentration data.

Of particular significance is the change in value of the modified Henry's law constant $\underline{H}'$ as the slope of the equilibrium curve changes. At partial pressures above 0.04 - 0.08 atmospheres the slope of the equilibrium curve changes but gradually, and the value of $\underline{H}'$ remains

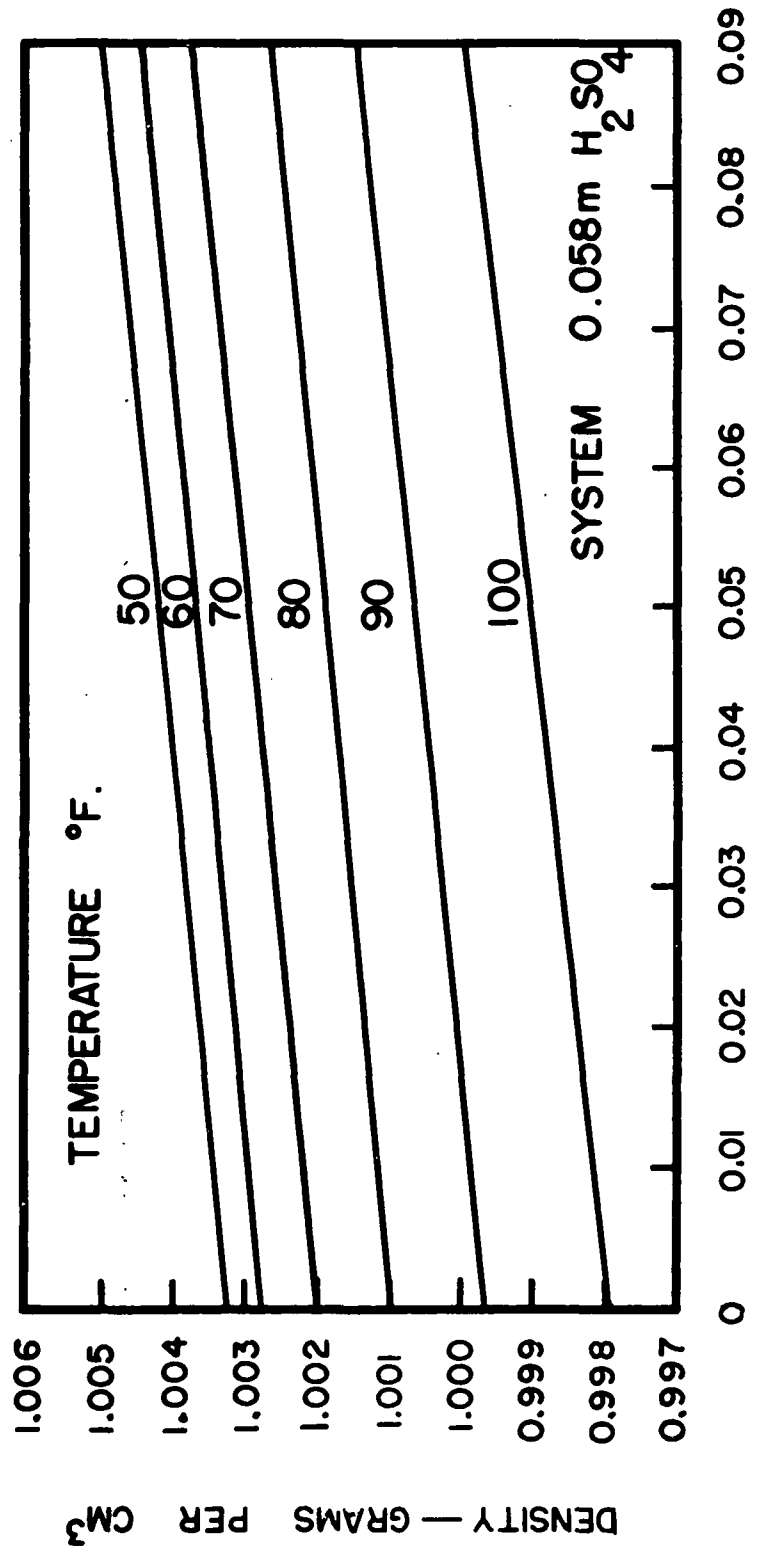


FIGURE 12. Density of Sulfur Dioxide—Dilute Aqueous Sulfuric Acid Solutions.

TABLE V

THE SOLUBILITY OF SULFUR DIOXIDE IN WATER AND DILUTE SOLUTIONS OF SULFURIC ACID, SODIUM BISULFITE, AND AMMONIUM BISULFITE

(Figures 13, 14, and 17)

A. SYSTEM: PURE WATER

50°F.

Run No.	1	2	3	11	12	13
p_{SO_2}, atm. x 10^2	0.5371	0.4401	0.2919	0.4799	0.08086	0.1926
C_{SO_2}, $\frac{\text{lb.-mols}}{\text{ft.}^3}$ x 10^3 *	1.667	1.442	1.187	1.643	0.5106	0.9120

50°F.

Run No.	35	36	37	65	66	67
p_{SO_2}, atm. x 10^2	0.9867	0.9161	0.6678	1.739	2.814	3.315
C_{SO_2}, $\frac{\text{lb.-mols}}{\text{ft.}^3}$ x 10^3 *	2.786	2.646	2.122	4.411	6.220	7.116

50°F.

Run No.	86	87	88
p_{SO_2}, atm. x 10^2	1.848	2.608	3.500
C_{SO_2}, $\frac{\text{lb.-mols}}{\text{ft.}^3}$ x 10^3 *	4.461	5.988	7.450

60°F.

Run No.	32	33	34
p_{SO_2}, atm. x 10^2	0.9789	0.9095	0.6586
C_{SO_2}, $\frac{\text{lb.-mols}}{\text{ft.}^3}$ x 10^3 *	2.248	2.142	1.679

70°F.

Run No.	14	15	16	17	18	19
p_{SO_2}, atm. x 10^2	0.2093	0.7338	0.1024	0.5070	0.4651	0.2005
C_{SO_2}, $\frac{\text{lb.-mols}}{\text{ft.}^3}$ x 10^3 *	0.6420	1.327	0.3260	1.161	1.090	0.5678

*Concentration of SO_2 is expressed as "total."

TABLE V (CONTINUED)

70°F. Run No.						
p_{SO_2}, atm. x10^2	20	21	22	59	60	61
	0.9831	0.9134	0.6603	1.724	2.796	3.486
C_{SO_2}, $\frac{lb.-mols}{ft.^3}$ x10^3 *	1.876	1.760	1.406	2.879	4.170	4.978

90°F. Run No.						
p_{SO_2}, atm. x10^2	26	27	28	38	39	40
	0.9524	0.8850	0.6409	1.102	0.8115	0.6334
C_{SO_2}, $\frac{lb.-mols}{ft.^3}$ x10^3 *	1.262	1.202	0.9182	0.1377	1.110	0.9207

90°F. Run No.						
p_{SO_2}, atm. x10^2	44	45	46	71	72	73
	0.4686	0.3622	0.1496	1.776	2.506	3.363
C_{SO_2}, $\frac{lb.-mols}{ft.^3}$ x10^3 *	0.7222	0.5800	0.3204	2.038	2.650	3.336

B. SYSTEM: 0.0580 MOLAL H_2SO_4

50°F. Run No.						
p_{SO_2}, atm. x10^2	56	58	68	69	70	89
	0.5048	0.1503	1.739	2.814	3.315	1.847
C_{SO_2}, $\frac{lb.-mols}{ft.^3}$ x10^3 *	0.8502	0.2550	3.072	4.980	5.882	3.293

50°F. Run No.		
p_{SO_2}, atm. x10^2	90	91
	2.607	3.498
C_{SO_2}, $\frac{lb.-mols}{ft.^3}$ x10^3 *	4.702	6.150

70°F. Run No.						
p_{SO_2}, atm. x10^2	23	24	25	50	51	52
	0.9831	0.9134	0.6615	0.4796	0.3393	0.1532
C_{SO_2}, $\frac{lb.-mols}{ft.^3}$ x10^3 *	1.145	1.018	0.7376	0.5030	0.4132	0.1710

*Concentration of SO_2 is expressed as "total."

TABLE V (CONTINUED)

70°F.

Run No.	64	77	78	79
p_{SO_2}, atm. x 10^2	3.490	1.1821	2.570	3.448
C_{SO_2}, $\frac{\text{lb.-mols}}{\text{ft.}^3}$ x 10^3 *	3.812	2.030	2.891	3.803

90°F.

Run No.	29	30	31	41	42	43
p_{SO_2}, atm. x 10^2	0.9524	0.8850	0.6409	1.102	0.8115	0.6334
C_{SO_2}, $\frac{\text{lb.-mols}}{\text{ft.}^3}$ x 10^3 *	0.7590	0.6000	0.4937	0.8008	0.6011	0.4656

90°F.

Run No.	74	75	76
p_{SO_2}, atm. x 10^2	1.776	2.506	3.363
C_{SO_2}, $\frac{\text{lb.-mols}}{\text{ft.}^3}$ x 10^3 *	1.261	2.045	2.438

C. SYSTEM: 0.0580 MOLAL $NaHSO_3$

70°F.

Run No.	80	81	82
p_{SO_2}, amt. x 10^2	1.830	2.583	3.466
C_{SO_2}, $\frac{\text{lb.-mols}}{\text{ft.}^3}$ x 10^3 *	5.502	6.447	7.374

D. SYSTEM: 0.0580 MOLAL NH_4HSO_3

70°F.

Run No.	83	84	85
p_{SO_2}, atm. x 10^2	1.830	2.583	3.466
C_{SO_2}, $\frac{\text{lb.-mols}}{\text{ft.}^3}$ x 10^3 *	5.128	6.087	7.146

*Concentration of SO_2 is expressed as "total."

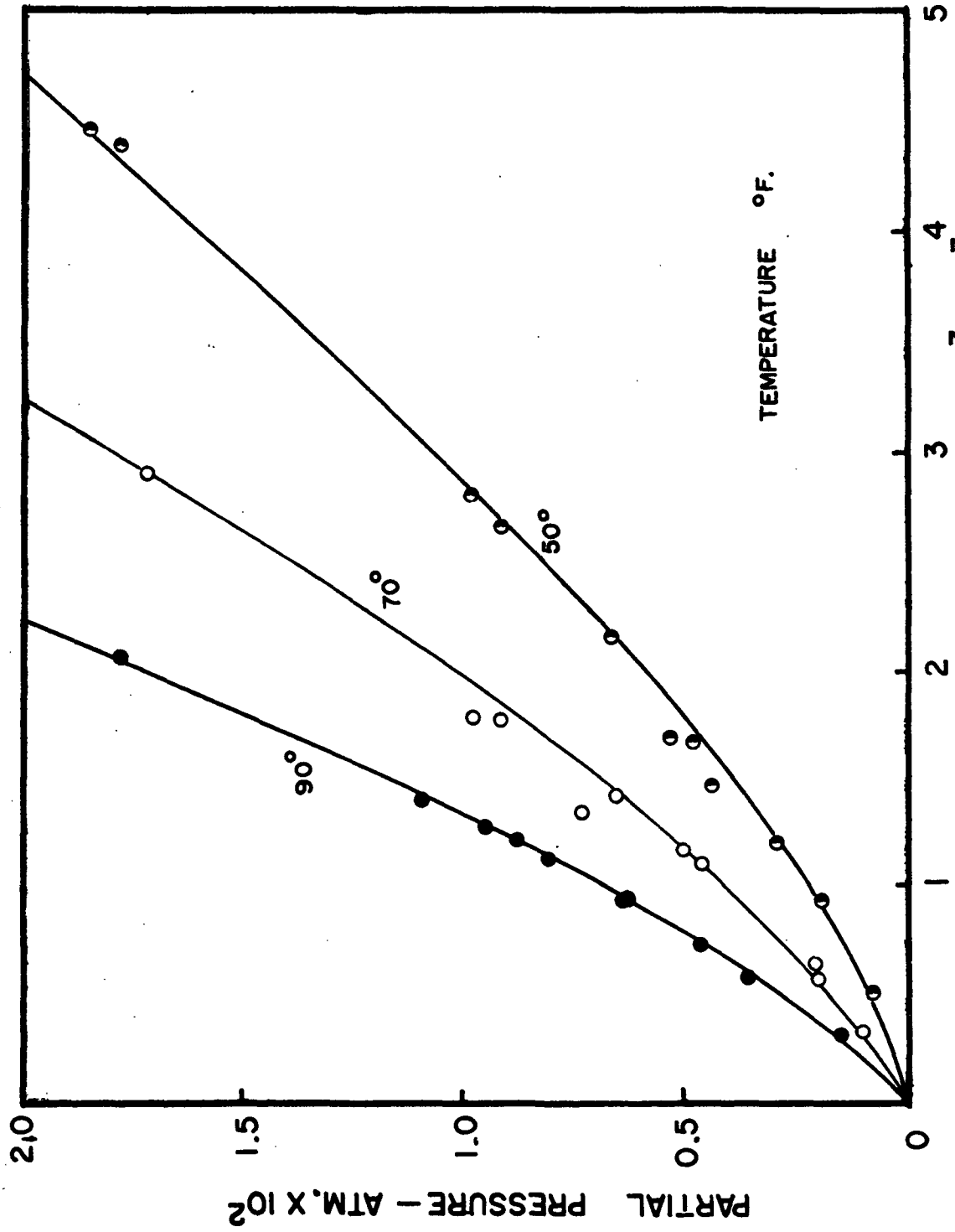


Figure 13. The Solubility of Sulfur Dioxide in Water at Low Partial Pressures.

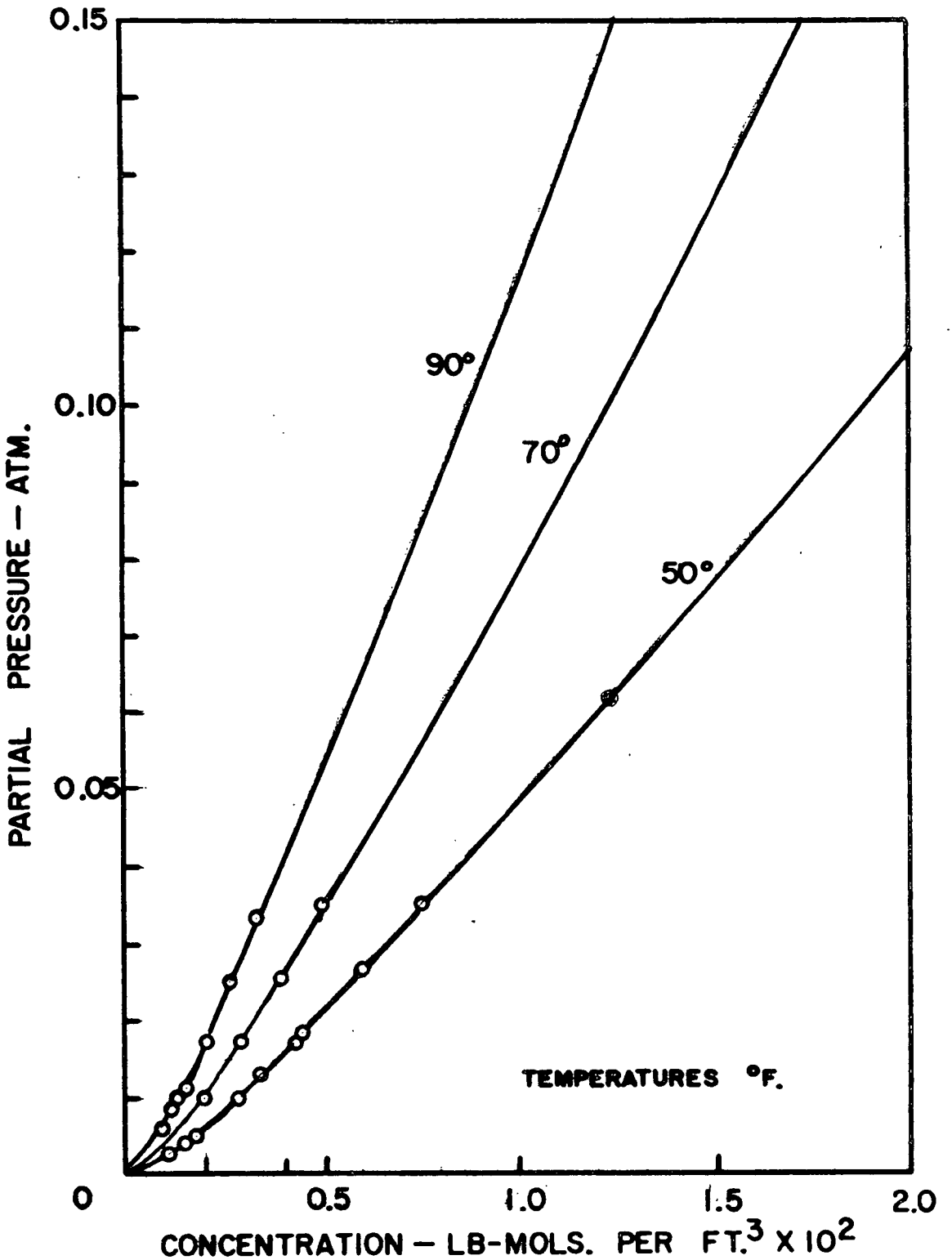


Figure 14. Alignment of Low-Concentration $SO_2 - H_2O$ Solubility Data with Those for High-Concentration.

The high-concentration curves are from cross-plotted data of White, Vivian and Whitney (62).

essentially constant over a wide range of operating conditions. Below 0.04, and particularly below 0.02 atm., the value of $\underline{H}'$ depends largely on the range of concentrations encountered in the tower operation. Also, the effect increases at lower temperatures. This situation can be better appreciated by comparing the values of $\underline{H}'$ as functions of concentration range for hypothetical tower operations. This is shown in Figure 15. It is clear that a modified Henry's law constant must be used with caution and this emphasizes the importance of choosing a short-packed height for studying the low-concentration range. At these low concentrations, a straight line fit to the equilibrium curve becomes poorer as the range of concentration becomes greater.

Johnstone and Leppla (54) have shown that the unhydrolyzed portion of sulfur dioxide in solution follows Henry's law. They established this by recomputing the conductivity data of Campbell and Maass (57) for sulfur dioxide solutions, applying a correction for the ionic strength. The values they report are given in Table VI and are shown plotted in terms of engineering units in Figure 16.

In their work, Whitney and Vivian (7) computed the unhydrolyzed portion by means of the ionization constant of Campbell and Maass (57). The Henry's law values thus obtained show fairly good agreement with those of Johnstone and Leppla. Table VII shows a comparison of values

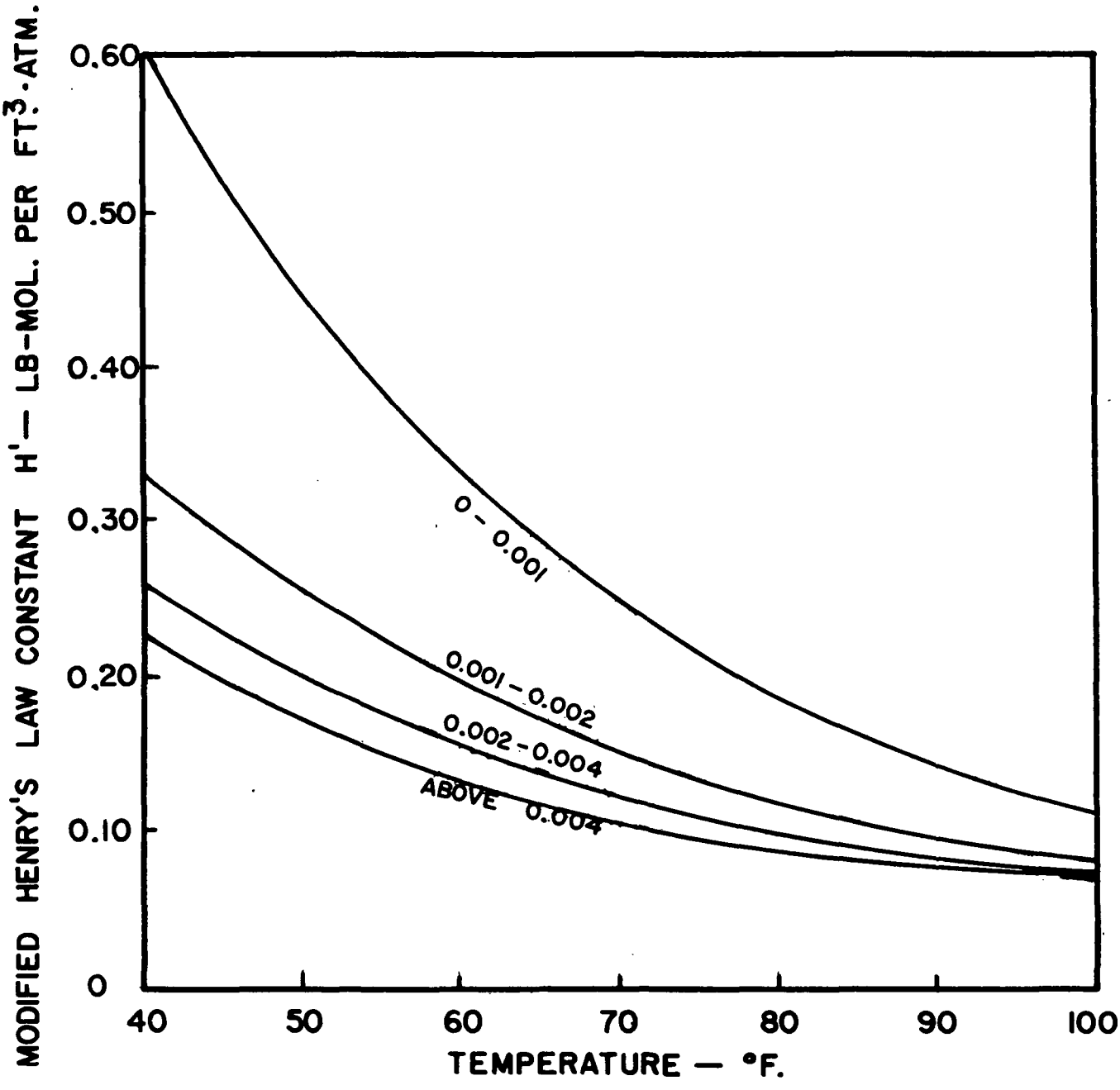


Figure 15. The Variation in the Modified Henry's Law Constant H' as a Function of the Concentration Range.

TABLE VI

THE EFFECT OF TEMPERATURE ON THE IONIZATION CONSTANT AND HENRY'S LAW CONSTANT OF SULFUROUS ACID (54)

(Figure 16)

Temperature, °C.	K	c_u/p Moles SO_2/1000 g. H_2O·atm.
0	0.0232	3.28
10	0.0184	2.20
18	0.0154	1.55
25	0.0130	1.23
35	0.0105	0.89
50	0.0076	0.56

at three temperatures. It appears that although interpolation of high concentration "total solubility" data to zero concentration involves uncertainties, a solubility curve could be calculated on the basis of the ionization constant, and the Henry's law constant for unhydrolyzed sulfur dioxide.

TABLE VII

COMPARISON OF THE HENRY'S LAW CONSTANT FOR UNHYDROLYZED SULFUR DIOXIDE FROM THE CALCULATION OF JOHNSTONE AND LEPPLA (54), AND CAMPBELL AND MAASS (57)

H_u lb.-mols SO_2/ft.^{3} atm.

Temperature, °F.	Johnstone and Leppla	Campbell and Maass	Difference, %
50	0.1352	0.1374	1.5
70	0.0873	0.0882	1.2
90	0.0552	0.0615	8.7

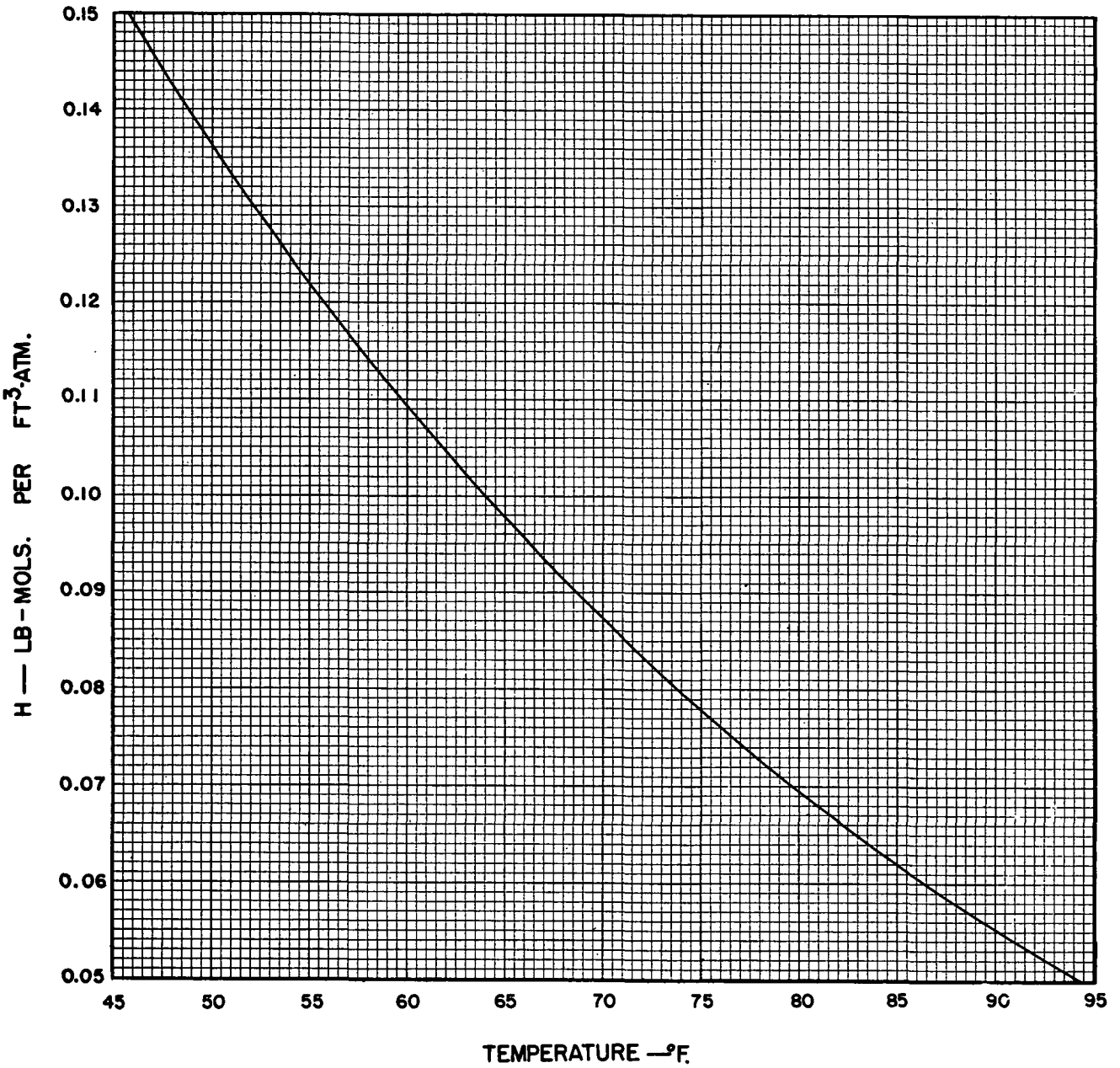


Figure 16. Henry's Law Constant for Nonionized Sulfur Dioxide in the System SO_2 – Water.
From the data of Johnstone and Leppla (54)

The values of Johnstone and Leppla have been adopted in this thesis since they are considered to be a refinement over those of Campbell and Maass.

Figure 17 presents the results of sulfur dioxide solubility determinations for 0.0580 molal sulfuric acid. The reciprocal of the slope of the curves (c/p) is much less than for the water system, indicating that the presence of acid has caused the hydrolysis of sulfur dioxide to be suppressed. Although the data are fitted very well by a straight line, the relationship should show some curvature since suppression is not complete. For the low concentration range of solute concentrations encountered in the absorption runs of this thesis, the sulfur dioxide is estimated to be from 70 to 85% hydrolyzed. For the high-concentration gas absorption runs, hydrolysis is between 30 and 40%. At 70°F. the presence of sulfuric acid of 0.0580 molal strength reduces the hydrolysis to 22.8%. The suppression by this strength acid is therefore incomplete, but the effect of suppression on the low-concentration system is quite marked. The use of higher concentrations of sulfuric acid would result in greater reduction in hydrolysis. On the basis of the data given by Johnstone and Leppla (54) at 25°C. (77°F.), 0.5174 molal acid would reduce the hydrolysis to 9.4% and 1.103 molal to 2.8%. The effect on viscosity and other flow properties of the liquor would be large and, for the low-concentration gas system, the amount of absorption would become small enough to jeopardize the accuracy of analysis.

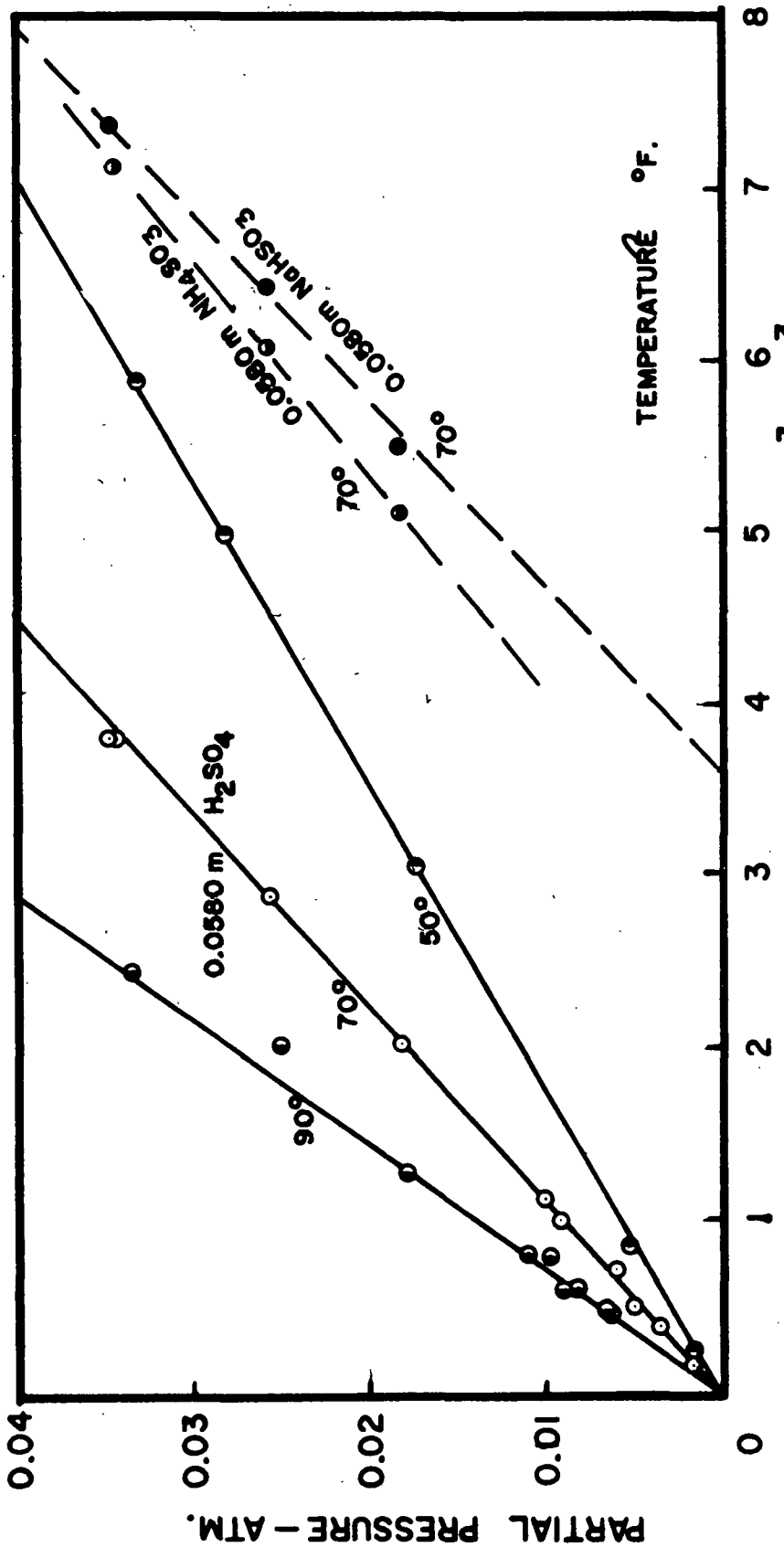


Figure 17. The Solubility of Sulfur Dioxide at Low Partial Pressure in 0.0580 Mdal Sulfuric Acid and Sodium and Ammonium Bisulfite Solutions.

A few solubility data for 0.0580 molal solutions of sodium and ammonium bisulfite were obtained at 70°F. and are shown plotted in Figure 17. The data are so meager as to allow few definite conclusions. If neither salt exhibited any back pressure at zero partial pressure, then the points should extrapolate to a value of 0.00361 lb.-mols/ft.^{3} (corresponding to 0.0580 molal). The sodium bisulfite data do allow fairly good extrapolation.

The displacement of the ammonium bisulfite points to the left of those of sodium bisulfite is puzzling. It might indicate the effect of stripping of ammonia from the solution during the solubility run or it might be that the line, straight at high concentrations (76), begins to curve toward the origin at partial pressures below 0.04 atmospheres. More low-concentration data are needed before concrete conclusions can be drawn.

C. RESULTS OF TOWER "CALIBRATION" RUNS

1. END EFFECTS

In conjunction with low-concentration sulfur dioxide-water absorption runs 414-420, end samples were taken at the base of the packing and at the tower outlet. These data are given in Table VIII and are plotted as end factors, $\underline{K_L a}/\underline{K_L ah}$, in Figure 18. A series of

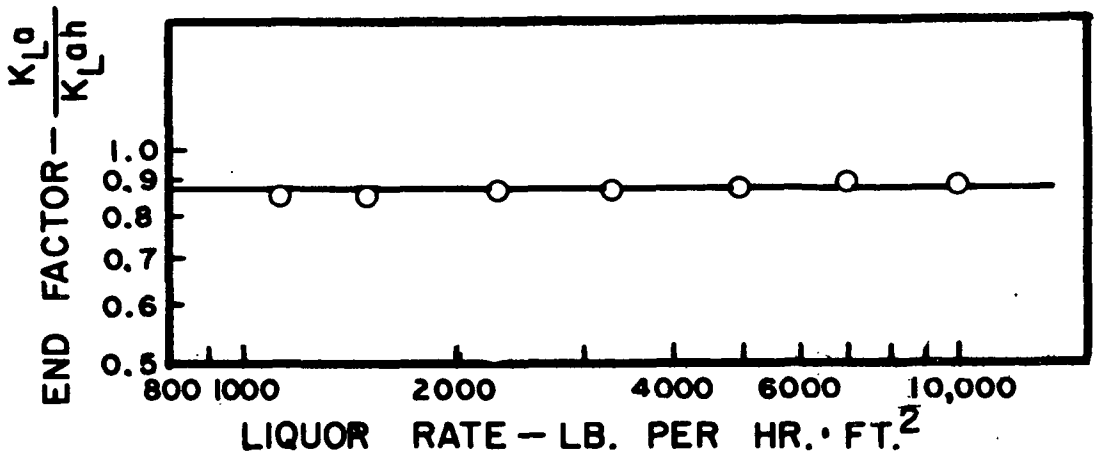


Figure 18. End Factor for 8-inch I.D. Tower Packed with 1 Foot

TABLE VIII

END FACTOR FOR 8-INCH I.D. TOWER PACKED WITH ONE FOOT OF 1-INCH CERAMIC RASCHIG RINGS. FACTOR DETERMINED BY END-SAMPLING LOW-CONCENTRATION SO_2-H_2O ABSORPTION RUNS AT 70°F.

(Figure 18)

Run No.	414	415	416	417	418	419	420
G, lb./hr.ft.^{2}	685	700	700	695	711	691	660
L, lb./hr.ft.^{2}	1130	1500	2280	3300	4990	7000	11,000
$K_L a$, hr.$^{-1}$	15.1	19.2	27.2	35.9	50.4	66.0	94.0
$K_L ah$, ft./hr.	18.0	22.5	31.3	41.2	57.0	73.7	106
End Factor	0.838	0.853	0.870	0.872	0.883	0.895	0.886

runs, not reported here, was also made on the effect at the top of the tower packing. The top end effect was found to be quite small, being on the order of 1% or less. Assuming this top end effect to be negligible, the straight line fit of the data of Table VIII gives an end factor of 0.87 for one foot of packing which corresponds to a fictitious packed height of 0.15 foot, which is the value employed in this thesis for correcting the absorption data. The plot of data in Figure 18 reveals the end effect to be a mild function of liquor rate, the effect decreasing with increase in liquor rate. These few data, and their precision, do not justify fitting a sloping line. Other investigators have found no significant effect of liquor rate on end effect (13, 15, 17).

2. DESORPTION OF OXYGEN

Figure 19 (Table IX) demonstrates that the desorption coefficient for oxygen from water is independent of the gas flow rate over a range of 35 to 700 lb./hr.ft.^{2}, which reaffirms the result of Sherwood and Holloway (20). This independence of desorption coefficient from gas rate is the criterion for accepting the oxygen-water system as one exhibiting an almost pure liquid-film resistance.

Figure 20 presents the results of desorption runs made at 70°F. with one and two feet of packed height over the range of liquor rates used

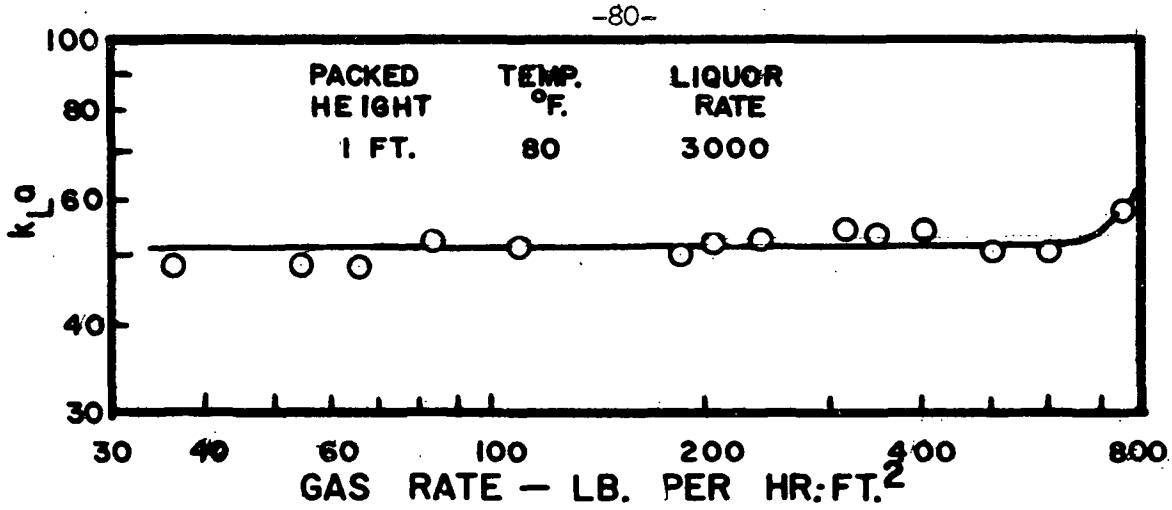


Figure 19. Oxygen Desorption Coefficient as a Function of Gas Flow Rate.

TABLE IX

DESORPTION COEFFICIENTS FOR OXYGEN FROM WATER AT A CONSTANT LIQUOR RATE (3000 lb./hr.ft.^{2}) AS A FUNCTION OF GAS RATE.

(Figure 19)

Run No.	89	90	91	92	93	94	95
$\underline{G}$, lb./hr.ft.^{2}	36.5	55.1	66.1	84.0	112	187	205
$k_L\underline{a}$, hr.$^{-1}$	48.6	48.6	48.1	52.4	51.9	50.5	51.9

Run No.	96	97	98	99	100	101	102
$\underline{G}$, lb./hr.ft.^{2}	241	317	349	408	508	604	771
$k_L\underline{a}$, hr.$^{-1}$	52.4	54.3	53.4	54.3	50.5	50.5	57.5

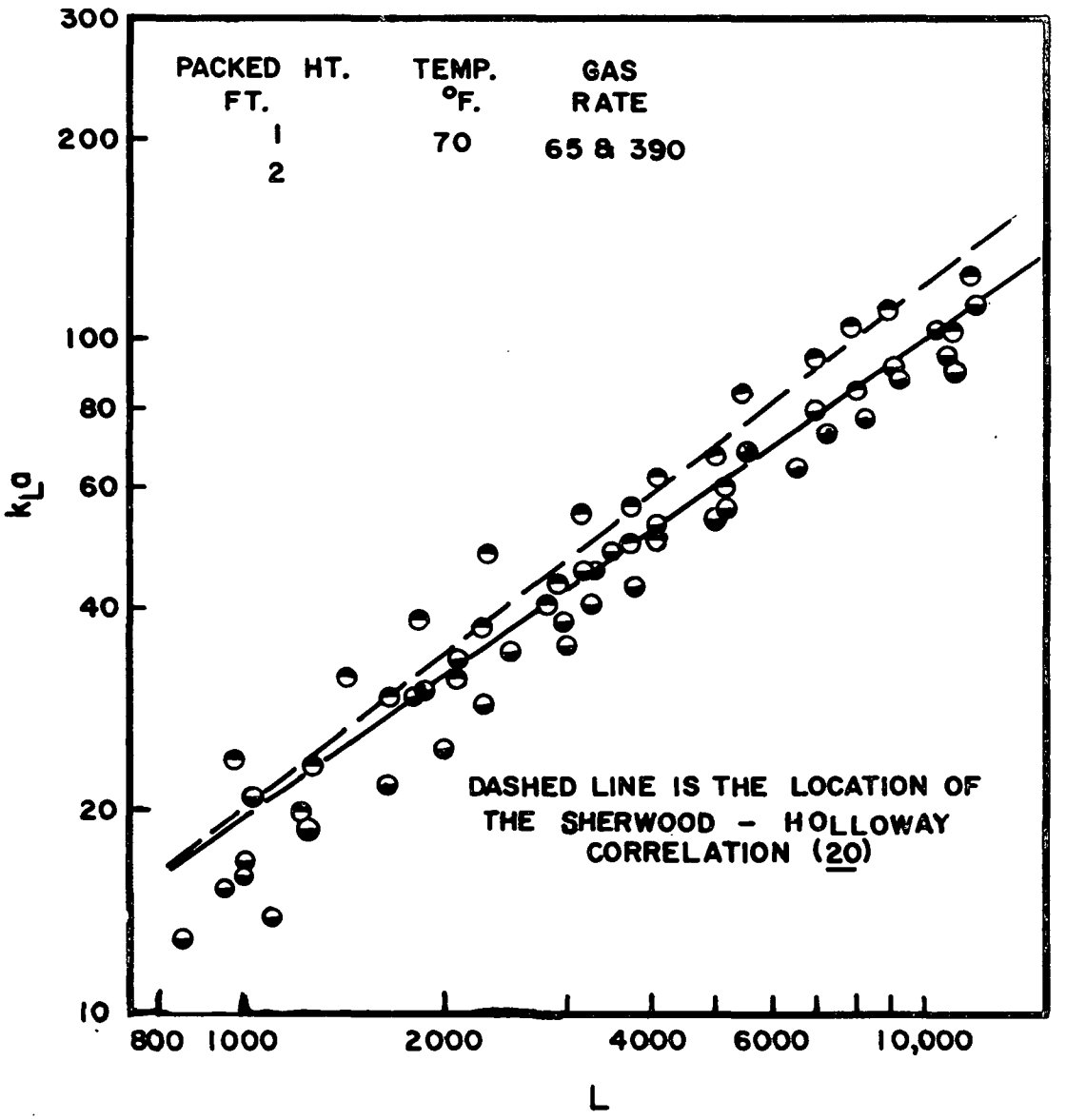


Figure 20. Oxygen Desorption Coefficient as a Function of Liquor Flow Rate.

in this thesis—700 to 11,000 lb./hr.ft.^{2} The complete data are given in Table XVII, APPENDIX I. The dashed line is that computed from the correlation of Sherwood and Holloway (20) for 1-inch ceramic Raschig rings:

$$\underline{K}_L\underline{a}/\underline{D}_L = 100\,[\underline{L}/M]^{0.78}\,[M/\underline{D}_L\rho]^{0.50} \qquad (28)$$

The value for the diffusivity of oxygen through water ($\underline{D}_L$) at 70°F. is 8.36 x 10^{-5} ft.^{2}/hr. It is the same value used by Sherwood and Holloway (7.75 x 10^{-5} ft.^{2}/hr. at 18°C.) corrected by means of the Stokes-Einstein equation (3)

$$\underline{D}_L = \underline{T}/\mu\underline{F} \qquad (29)$$

The line of best fit for the oxygen desorption data lies below the Sherwood and Holloway line. The slope of the line is 0.71 compared to 0.78 for that of Sherwood and Holloway. At $\underline{L}$ = 1000 lb./hr.ft.^{2} the value is 98% as large and at $\underline{L}$ = 10,000 it is only 84.8% that of the predicted value. This amount of disagreement is not disturbing although it is greater than was expected. The difference is assumed to be attributable to differences in the nature of liquor flow and distribution between the two towers. The data for two feet of packed height show consistently low values. No adequate explanation has been found for this.

3. ABSORPTION OF HIGH-CONCENTRATION SULFUR DIOXIDE

Results of 15 high-concentration sulfur dioxide-water absorption runs made at 70°F. and two feet of packed height are shown in Figure 21 (Table X). The purpose of these runs was to determine whether the tower used could duplicate Whitney's and Vivian's (7) data for the absorption of high-concentration gases. The data agree rather well at low liquor rate, but at the higher rates they fail to agree by about 10%. The agreement between data is somewhat poorer than is indicated in Figure 21 since the oxygen desorption coefficients for this thesis are lower than were those for the tower used by Whitney and Vivian. Although the disagreement is significant, it is not of serious proportions.

D. THE ABSORPTION OF LOW-CONCENTRATION SULFUR DIOXIDE INTO WATER

1. RUNS AT 70°F.

Figure 22 shows the plot of low-concentration absorption data for 70°F. Table XI gives a summary of these data.* Included in Figure 22 are smoothed values of HTU curves and in Figure 23 smoothed curves for constant gas rate versus variable liquor rate.

*The complete data are given in Table XVIII, APPENDIX I.

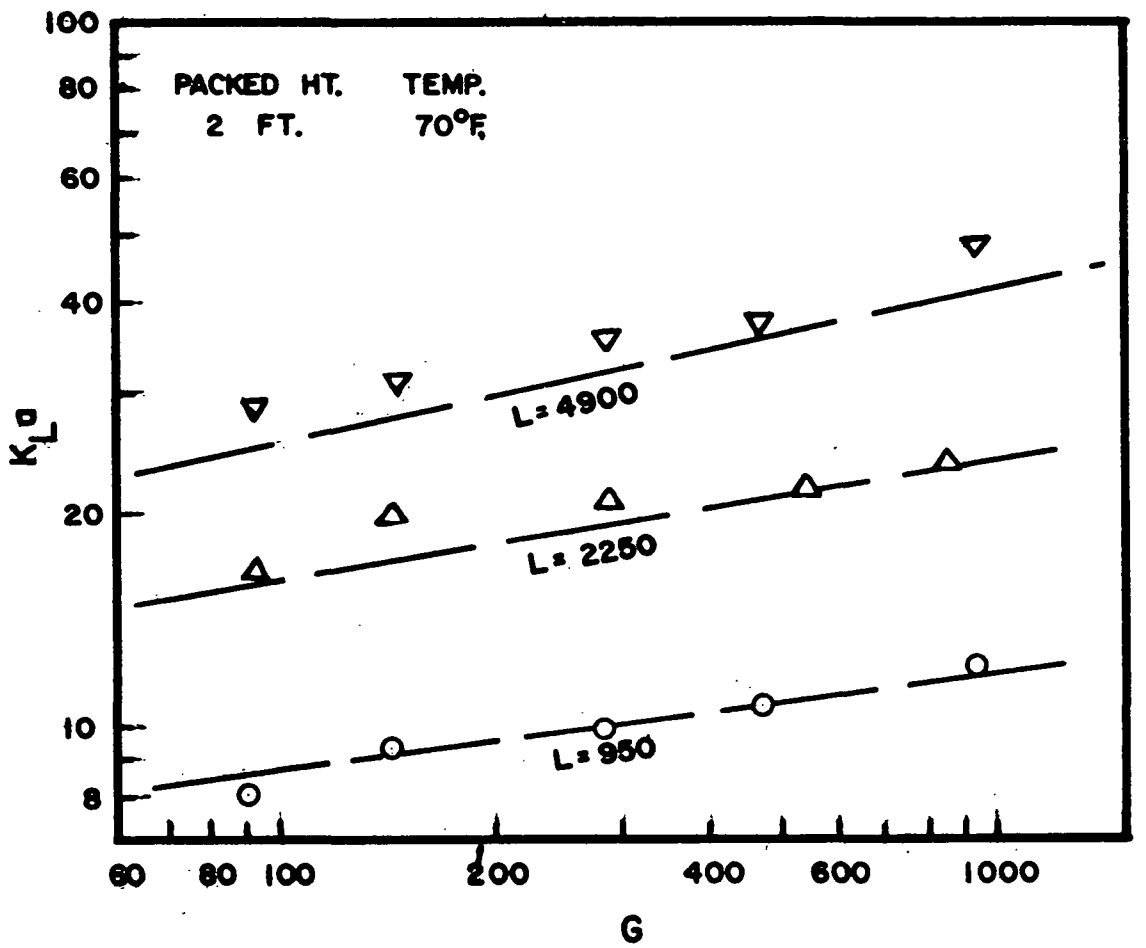


Figure 21. Over — All Absorption Coefficients for High — Concentration Sulfur Dioxide Gases into Water.

Dashed line represents data of Whitney and Vivian (7)

TABLE X

SUMMARY OF HIGH-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 70°F.

(Figure 21)

Run No.	55	56	57	58	59	60	61	62
$\underline{L}$, lb./hr. ft.^{2}	949	949	949	949	949	2110	2340	2400
$\underline{c}_1$, lb./mol./ft.^{3}	0.00450	0.00564	0.00617	0.00740	0.0145	0.00720	0.00656	0.00770
$\underline{G}$, lb./hr. ft.^{2}	87.5	144	284	470	942	94.2	140	288
$\underline{p}_1$, atm.	0.05940	0.06610	0.0677	0.0786	0.1670	0.121	0.0974	0.101
$\underline{p}_2$, atm.	0.0317	0.0457	0.0555	0.0708	0.157	0.0595	0.0537	0.0835
$(\underline{K}_L\underline{a})_n$, hr.$^{-1}$	8.17	9.30	9.95	10.7	12.1	16.8	20.5	21.6
$(\underline{K}_L\underline{a})_p$, hr.$^{-1}$	12.6	13.6	15.0	12.8	16.0	23.7	30.0	28.9
$(\underline{k}_G\underline{a})$	2.82	4.14	4.97	8.40	16.6	4.82	5.72	9.00
$\underline{H}'$, lb.-mol./ft.^{3} atm.	0.104	0.107	0.0980	0.105	0.0790	0.104	0.105	0.105
$(\underline{k}_L\underline{a})_n$	11.8	12.2	12.3	12.3	13.2	26.4	32.8	28.9
$(\underline{k}_L\underline{a})_p$	20.7	19.1	20.4	14.7	15.5	41.6	55.5	40.2
$(\underline{r}_L/\underline{R}_L)_n$	0.693	0.762	0.808	0.869	0.916	0.637	0.625	0.747

TABLE X (continued)

SUMMARY OF HIGH-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 70°F.

Run No.	63	64	65	66	67	68	69
$\underline{L}$	2260	2240	4900	4870	4910	4900	4910
$\underline{c}_1$	0.00959	0.00992	0.00540	0.00605	0.00512	0.00678	0.00625
$\underline{G}$	541	851	86.9	141	282	465	931
$\underline{p}_1$	0.120	0.118	0.1406	0.1287	0.0808	0.0993	0.0753
$\underline{p}_2$	0.0968	0.103	0.0234	0.0396	0.0437	0.0666	0.0539
$(\underline{K}_L\underline{a})_n$	21.8	23.8	28.8	31.9	35.8	37.6	48.7
$(\underline{K}_L\underline{a})_p$	29.6	31.0	43.7	45.6	50.4	52.7	66.8
$\underline{k}_G\underline{a}$	15.0	27.4	5.57	8.73	12.7	17.5	--
$\underline{H}'$	0.105	0.101	0.105	0.105	0.107	0.105	0.107
$(\underline{k}_L\underline{a})_n$	25.7	26.1	63.0	51.8	53.2	48.5	--
$(\underline{k}_L\underline{a})_p$	35.6	34.4	92.5	84.0	77.5	71.5	--
$(\underline{r}_L/\underline{R}_L)_n$	0.848	0.912	0.457	0.616	0.673	0.775	--

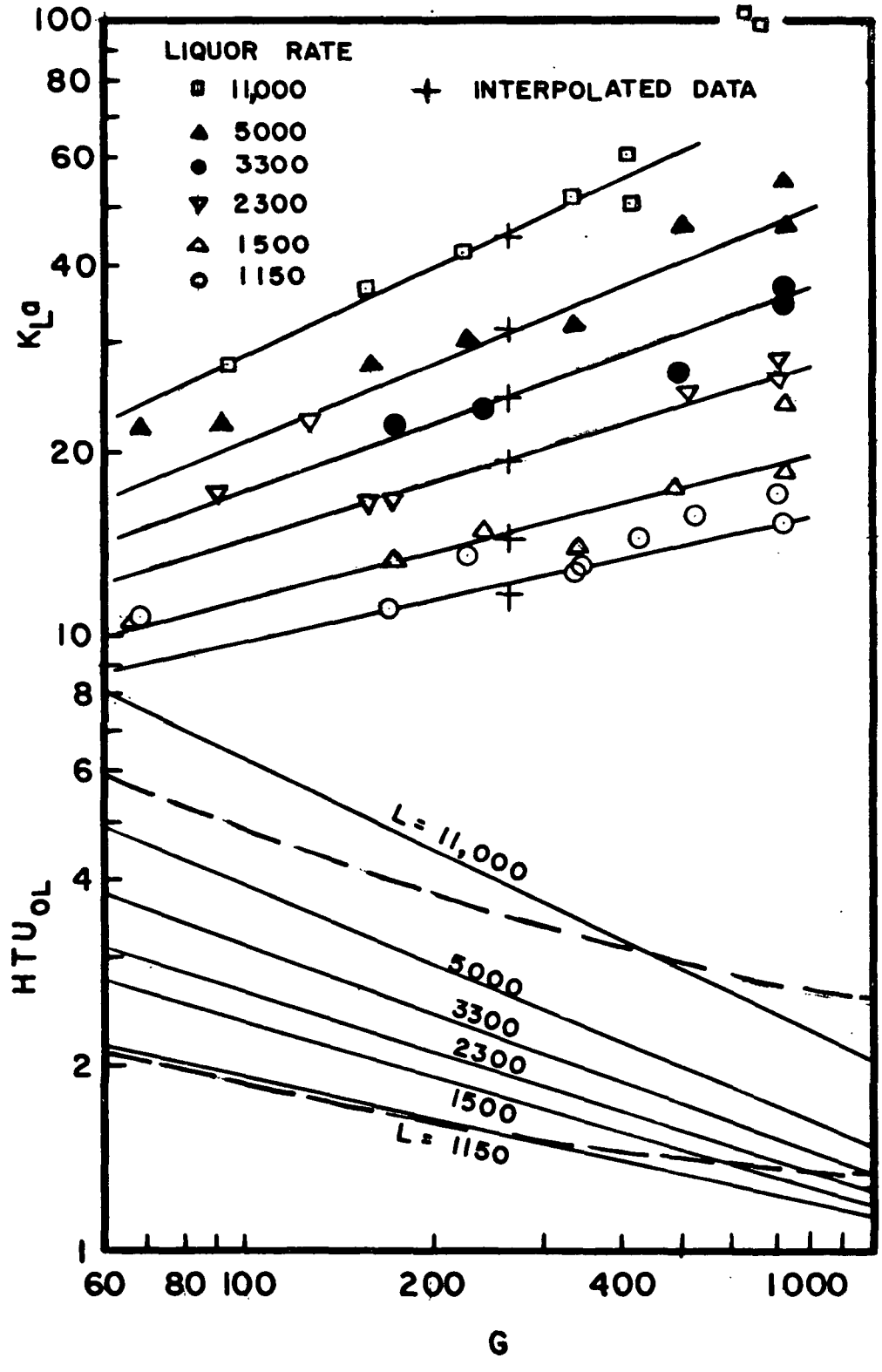


Figure 22. The Over-All Absorption Coefficients for Low-Concentration Sulfur Dioxide into Water.

Dashed lines are HTU values of Whitney and Vivian (7) for liquor rates of 1150 and 11,000 lb./hr. ft.^{2}

TABLE XI

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 70°F.

(Figure 22)

Run No.	282	249	318	327	261	262	337	269	270
$\underline{L}$, lb./hr. ft.^{2}	800	1050	1120	1130	1120	1120	1130	1120	1120
$\underline{c}_1$, lb.-mol./ft.^{3}	0.00124	0.00117	0.000569	0.000491	0.000597	0.000856	0.000584	0.000683	0.000596
$\underline{G}$, lb./hr. ft.^{2}	278	424	68	173	226	338	342	522	725
$\underline{p}_1$, atm. x 10^2	0.795	1.07	0.596	0.451	0.485	0.777	0.459	0.472	0.411
$\underline{p}_2$, atm. x 10^2	0.629	0.862	0.380	0.310	0.374	0.679	0.369	0.421	0.352
$(\underline{K}_L\underline{a})_n$	5.33	13.6	10.4	10.9	13.2	12.5	12.8	15.3	14.9
Std. $\underline{L}$	--	1150	1150	1150	1150	1150	1150	1150	1150
$(\underline{K}_L\underline{a})_n$ at Std. $\underline{L}$	--	14.1	10.6	11.0	13.4	12.7	12.9	15.5	15.1
$(\underline{K}_L\underline{a})_p$	20.5	27.6	--	--	--	--	--	--	--
$\underline{k}_G\underline{a}$	5.27	7.86	3.04	4.22	5.63	7.15	7.25	9.35	12.9
$\underline{H}'$	0.148	0.139	0.166	0.182	0.174	0.150	0.174	0.159	0.185
$(\underline{k}_L\underline{a})_n$	6.30	17.9	24.1	20.5	22.4	16.9	18.5	20.6	18.2
$(\underline{k}_L\underline{a})_p$	31.1	--	--	--	--	--	--	--	--

TABLE XI (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 70°F.

(Figure 22)

Run No.	414	274	216	248	283	311	319	328	333	339
$\underline{L}$, lb./hr. ft.^{2}	1130	1170	1350	1340	1340	1360	1540	1500	1490	1510
$\underline{c}_1$, lb.-mol./ft.^{3}	0.00139	0.000441	0.000623	0.00145	0.00128	0.000743	0.000365	0.000377	0.000440	0.000440
$\underline{G}$, lb./hr. ft.^{2}	710	278	272	424	278	278	68	173	240	342
$\underline{p}_1$, atm. x 10^2	1.30	0.407	0.961	1.59	0.909	0.473	0.532	0.370	0.380	0.387
$\underline{p}_2$, atm. x 10^2	1.09	0.280	0.902	1.26	0.681	0.342	0.200	0.218	0.262	0.300
$(\underline{K}_L\underline{a})_n$	16.9	11.0	7.82	15.4	14.4	12.7	10.4	13.3	14.7	14.0
Std. $\underline{L}$	1150	--	--	--	--	--	1500	1500	1500	1500
$(\underline{K}_L\underline{a})_n$ at Std. $\underline{L}$	17.0	--	--	--	--	--	10.2	13.3	14.8	13.9
$(\underline{K}_L\underline{a})_p$	--	30.1	16.3	--	29.0	31.4	--	--	--	--
$\underline{k}_G\underline{a}$	13.1	6.37	6.82	9.08	6.88	6.86	3.52	5.45	6.62	8.32
$\underline{H}'$	0.137	0.188	0.135	0.132	0.143	0.178	0.179	0.202	0.194	0.191
$(\underline{k}_L\underline{a})_n$	20.5	16.3	9.25	19.8	20.6	19.1	22.1	26.2	25.8	20.6
$(\underline{k}_L\underline{a})_p$	--	51.3	20.6	39.4	45.5	90.0	--	--	--	--

TABLE XI (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 70°F.

(Figure 22)

Run No.	342	345	415	247	215	312	284	252	255	329
$\underline{L}$, lb./hr. ft.^{2}	1500	1510	1500	1850	1870	1910	1930	2290	2290	2280
$\underline{c}_1$, lb.-mol./ft.^{3}	0.000820	0.000859	0.00135	0.00130	0.000359	0.000651	0.00123	0.000471	0.000364	0.000328
$\underline{G}$, lb./hr. ft.^{2}	492	731	730	424	272	278	277	91.5	158	173
$\underline{p}_1$, atm. x 10^2	0.713	0.694	1.26	1.51	0.285	0.474	0.994	0.754	0.718	0.393
$\underline{p}_2$, atm. x 10^2	0.594	0.608	1.17	1.08	0.107	0.290	0.661	0.261	0.214	0.200
$(\underline{K}_L\underline{a})_n$	17.3	18.6	20.7	20.2	24.9	15.0	17.1	16.9	16.4	16.5
Std. $\underline{L}$	1500	1500	1500	--	--	--	--	2300	2300	2300
$(\underline{K}_L\underline{a})_n$ at Std. $\underline{L}$	17.3	18.6	23.8	--	--	--	--	17.0	16.5	16.6
$(\underline{K}_L\underline{a})_p$	--	--	--	38.4	25.4	39.0	36.4	--	--	--
$\underline{k}_G\underline{a}$	10.9	15.6	15.6	10.7	7.88	7.96	8.00	4.53	6.10	6.43
$\underline{H}'$	0.154	0.157	0.135	0.132	0.238	0.188	0.145	0.167	0.155	0.204
$(\underline{k}_L\underline{a})_n$	18.6	22.9	25.2	26.9	--	23.3	24.8	20.5	28.1	34.7
$(\underline{k}_L\underline{a})_p$	--	--	--	56.1	36.6	68.5	60.2	--	--	--

TABLE XI (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 70°F.

(Figure 22)

Run No.	260	268	271	416	275	214	313	285	246	276
$\underline{L}$, lb./hr.ft.^{2}	2290	2290	2290	2280	2350	2470	2610	2670	2640	3220
$\underline{c}_1$, lb.-mol./ft.^{3}	0.000657	0.000795	0.000632	0.00118	0.000609	0.000408	0.000646	0.00142	0.00104	0.000575
$\underline{G}$, lb./hr. ft.^{2}	226	522	725	730	278	272	278	277	424	278
$\underline{p}_1$, atm. x 10^2	0.651	0.780	0.526	1.14	0.656	0.447	0.528	1.45	1.35	0.777
$\underline{p}_2$, atm. x 10^2	0.518	0.592	0.422	0.905	0.474	0.266	0.278	0.876	0.848	0.491
$(\underline{K}_L\underline{a})_n$	22.4	24.6	26.1	28.2	21.5	20.2	19.1	20.1	25.3	24.6
Std. $\underline{I}$	2300	2300	2300	2300	23.0	—	—	—	—	3300
$(\underline{K}_L\underline{a})_n$ at Std. $\underline{I}$	22.5	25.0	26.2	28.3	21.2	—	—	—	—	24.8
$(\underline{K}_L\underline{a})_p$	—	—	—	—	49.0	51.7	49.2	39.2	49.5	54.0
$\underline{k}_G\underline{a}$	7.55	13.7	20.3	20.3	8.65	8.82	9.06	9.06	12.4	9.60
$\underline{H}'$	0.156	0.151	0.163	0.135	0.150	0.185	0.179	0.145	0.138	0.155
$(\underline{k}_L\underline{a})_n$	41.7	34.8	33.3	34.6	47.6	35.0	30.6	29.6	35.2	41.0
$(\underline{k}_L\underline{a})_p$	—	—	—	—	97.0	108	93.5	62.8	76.2	106

TABLE XI (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 70°F.

(Figure 22)

Run No.	322	251	256	259	264	267	272	418	212
L, lb./hr. ft.^{2}	4940	5000	5000	5000	5000	5000	5000	4990	
c_1, lb.-mol./ft.^{3}	0.000315	0.000292	0.000473	0.000459	0.000467	0.000559	0.000628	0.000766	
G, lb./hr.ft.^{2}	68	91.5	158	226	338	500	725	731	
p_1, atm. x 10^2	1.10	0.873	1.03	0.816	0.727	0.664	0.597	0.873	
p_2, atm. x 10^2	0.119	0.150	0.356	0.395	0.425	0.403	0.383	0.615	
$(K_La)_n$	21.8	22.0	27.7	30.3	32.2	43.3	55.2	47.7	
Std. L	5000	5000	5000	5000	5000	5000	5000	5000	--
$(K_La)_n$ at Std. L	22.0	22.0	27.7	30.3	32.2	43.3	55.2	47.8	--
$(K_La)_p$	--	--	--	--	--	--	--	--	--
k_Ga	5.20	5.74	7.83	9.55	12.8	18.2	29.4	29.4	
H	0.169	0.172	0.145	0.157	0.160	0.165	0.168	0.150	
$(k_La)_n$	74.5	70.0	56.7	60.6	54.0	72.0	80.5	63.3	
$(k_La)_p$	--	--	--	--	--	--		--	--

TABLE XI (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 70°F.

(Figure 22)

Run No.	321	330	334	343	417	346	213	245	286	314	277
L, lb./hr. ft.^{2}	3320	3300	3310	3300	3300	3300	3700	3700	3720	3820	4400
c_1, lb. mol./ft.^{3}	0.000186	0.000302	0.000370	0.000595	0.000987	0.000531	0.000456	0.00100	0.00136	0.000537	
G, lb./hr.ft.^{2}	68	173	240	492	724	724	272	424	277	278	269
p_1, atm. x 10^2	0.530	0.441	0.592	0.700	1.05	0.448	0.569	1.49	1.58	0.568	
p_2, atm. x 10^2	0.147	0.167	0.300	0.511	0.790	0.335	0.329	0.864	0.800	0.250	
$(K_L a)_n$	11.9	22.1	23.6	26.6	35.8	34.9	28.2	31.4	25.8	19.2	
Std. I		3300	3300	3300	3300	3300	--	--	--	--	
$(K_L a)_n$ at Std. I		22.1	23.5	26.6	35.8	34.9	--	--	--	--	
$(K_L a)_p$		--	--	--	--	--	70.3	60.5	46.3	53.7	
$k_G a$		7.25	8.88	15.7	24.4	24.4	10.0	14.1	10.0	10.0	11.0
H'		0.202	0.176	0.157	0.141	0.180	0.174	0.135	0.145	0.180	0.152
$(k_L a)_n$		27.7	44.3	36.2	45.0	47.0	55.3	45.0	41.2	29.2	61.0
$(k_L a)_p$		--	--	--	--	--	182	97.0	77.5	100	114

TABLE XI (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 70°F.

(Figure 22)

Run No.	212	287	315	244	278	323	419
$\underline{L}$, lb./hr. ft.^{2}	5200	5280	5300	5400	5500	7050	7000
$\underline{c}_1$, lb.-mol./ft.^{3}	0.000420	0.00120	0.000465	0.000854	0.000537	0.000226	0.000628
$\underline{G}$, lb./hr. ft.^{2}	272	277	278	424	278	68	708
$\underline{p}_1$, atm. x 10^2	0.659	1.75	0.611	1.47	0.830	0.607	0.703
$\underline{p}_2$, atm. x 10^2	0.316	0.554	0.206	0.799	0.456	0.116	0.392
$(\underline{K}_L\underline{a})_n$	30.9	32.2	25.0	34.7	30.0	22.5	64.8
Std. $\underline{I}$	--	--	--	--	--	--	--
$(\underline{K}_L\underline{a})_n$ at Std. $\underline{I}$	--	--	--	--	--	--	--
$(\underline{K}_L\underline{a})_p$	88.5	48.1	66.2	76.8	65.0	--	--
$\underline{k}_G\underline{a}$	10.8	10.9	10.8	16.0	12.7	5.66	33.4
$\underline{H}'$	0.170	0.138	0.183	0.137	0.156	0.196	0.162
$(\underline{k}_L\underline{a})_n$	30.9	54.3	25.0	45.9	52.4	101	94.0
$(\underline{k}_L\underline{a})_p$	238	78.0	143	136	133	--	--

TABLE XI (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 70°F.

(Figure 22)

Run No.	279	243	211	316	288	280	250	257	258	289
$\underline{L}$, lb./hr. ft.^{2}	7600	7600	7750	7750	7800	9400	11,000	11,000	11,000	11,100
$\underline{c}_1$, lb.-mol./ft.^{3}	0.000337	0.000686	0.000331	0.000382	0.000884	0.000274	0.000114	0.000628	0.000290	0.000715
$\underline{G}$, lb./hr. ft.^{2}	278	424	272	272	277	281	94.6	158	226	270
$\underline{p}_1$, atm. x 10^2	0.678	1.48	0.698	0.673	1.45	0.630	0.627	1.89	0.880	1.41
$\underline{p}_2$, atm. x 10^2	0.303	0.495	0.290	0.145	0.234	0.243	0.0682	1.68	0.275	0.116
$(\underline{K}_L\underline{a})_n$	38.4	50.2	37.1	31.2	49.5	40.5	27.3	36.7	41.9	59.8
Std. $\underline{L}$	---	--	--	--	--	--	11,000	11,000	11,000	11,000
$(\underline{K}_L\underline{a})_n$ at Std. $\underline{L}$	--	--	--	--	--	--	27.3	36.7	41.9	59.7
$(\underline{K}_L\underline{a})_p$	90.0	102	94.0	82.0	104	106	--	--	--	150
$\underline{k}_G\underline{a}$	10.5	17.5	11.7	11.7	11.7	12.1	48.0	9.25	11.0	12.3
$\underline{H}'$	0.169	0.142	0.168	0.188	0.152	0.177	0.197	0.145	0.163	0.160
$(\underline{k}_L\underline{a})_n$	100	84.6	75.0	63.0	139	99	33.4	87.0	111	--
$(\underline{k}_L\underline{a})_p$	370	208	322	208	480	455	--	--	--	625

TABLE XI (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 70°F.

(Figure 22)

Run No.	210	317	281	265	242	266	273	420
L, lb./hr. ft.^{2}	11,000	11,200	11,100	11,000	11,000	11,000	11,000	11,000
c_1, lb.-mol./ft.^{3}	0.000270	0.000317	0.000209	0.000317	0.000531	0.000373	0.000424	0.000459
G, lb./hr. ft.^{2}	272	272	278	338	424	420	640	675
p_1, atm. x 10^2	0.662	0.634	0.613	0.692	1.50	0.713	0.512	0.564
p_2, atm. x 10^2	0.223	0.0788	0.201	0.261	0.533	0.266	0.159	0.189
$(K_L a)_n$	46.3	46.7	37.6	51.8	50.5	60.5	104	98.4
Std. I	11,000	11,000	11,000	11,000	11,000	11,000	11,000	11,000
$(K_L a)_n$ at Std. I	46.3	46.7	37.5	57.8	50.5	60.5	104	98.4
$(K_L a)_p$	125	63.4	104	--	107	--	--	--
$k_G a$	12.0	12.3	12.3	15.0	18.8	19.0	29.2	35.3
H'	0.179	0.200	0.184	0.172	0.141	0.172	0.197	0.188
$(k_L a)_n$	149	--	86.2	114	81.3	133	344	--
$(k_L a)_p$	1370	195	400	--	212	--	--	--

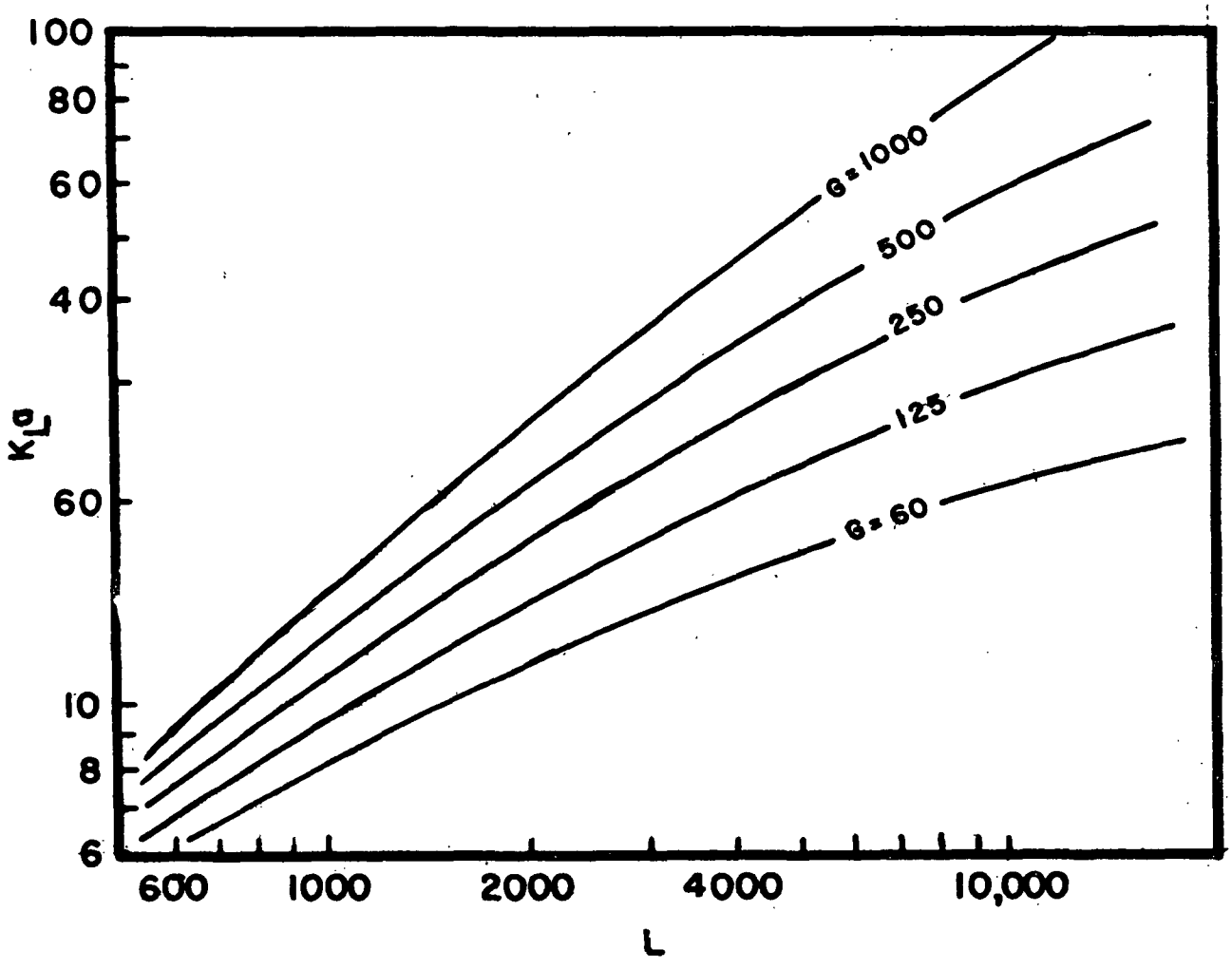


FIGURE 23. The Over – All Absorption Coefficients for Low – Concentration Sulfur Dioxide into Water at 70 ° F.

The variability of the data for low-concentration gas absorption at first appears disturbing, but it is in the nature of low-concentration over-all coefficient data to show variance. This state of affairs arises as a consequence of the additivity of the two-film theory (See Equation 8, page 8) and the variability of the modified Henry's law constant discussed in Part B of this section. If it may be assumed that the individual liquid film coefficient, $\underline{k}_L\underline{a}$, is independent of solute concentration level, then the values of the over-all absorption coefficient $\underline{K}_L\underline{a}$ for low and high concentrations cannot be the same.

$$1/\underline{K}_L\underline{a} = 1/\underline{k}_L\underline{a} + \underline{H}'/\underline{k}_G\underline{a} \qquad (8)$$

In the range of high gas concentrations (10-20%) $\underline{H}'$ will have an average value near 0.10 at 70°F. Whitney and Vivian (7) used an average value of 0.107. Table X shows the values of $\underline{H}'$ for the high-concentration runs of this thesis. Although they vary some, the average seems to be near 0.105.

For the case of low-concentration gases, the values of $\underline{H}'$ are greater and vary according to the concentration region of the solubility curve involved in the tower run. One generalization can be made and that is that the over-all coefficient for low-concentration gases will be less than for high-concentration gases for the same conditions of phase flow rates. This is a consequence of rearranging Equation (8) to the form

$$\frac{K}{L}a = \frac{k}{L}a \cdot \frac{k}{G}a / \frac{k}{G}a + \underline{H'}\frac{k}{L}a \qquad (30)$$

At high gas rates, $\frac{k}{G}a$ minimizes the effect of differences in $\underline{H'}$. Therefore, it is expected that the over-all coefficients would be nearly equal at high gas rates and should show the greatest difference at low gas rates. Figure 24 shows this to be true by the difference in slope between high-and low-concentration data for constant liquor rate.

2. RUNS AT 50 AND 90°F.

Only a few runs were made at 50 and 90°F. for absorption of low-concentration gases into water. Figure 25 gives the plot of data which are presented in Tables XII and XIII. At low temperature the difference in $\underline{H'}$ values for low- and high-concentration gas absorption should be greater than the difference in $\underline{H'}$ at higher temperatures; therefore the over-all coefficients should show better agreement at 90°F. than they do at 50°F. Figure 26 compares the results. The results are consistent if it is assumed that the data of Whitney and Vivian (7), used in Figure 26, would show the same difference between high-concentration data obtained in this tower at 50 and 90°F.

The results are in general agreement with the two-film theory for pure physical absorption.

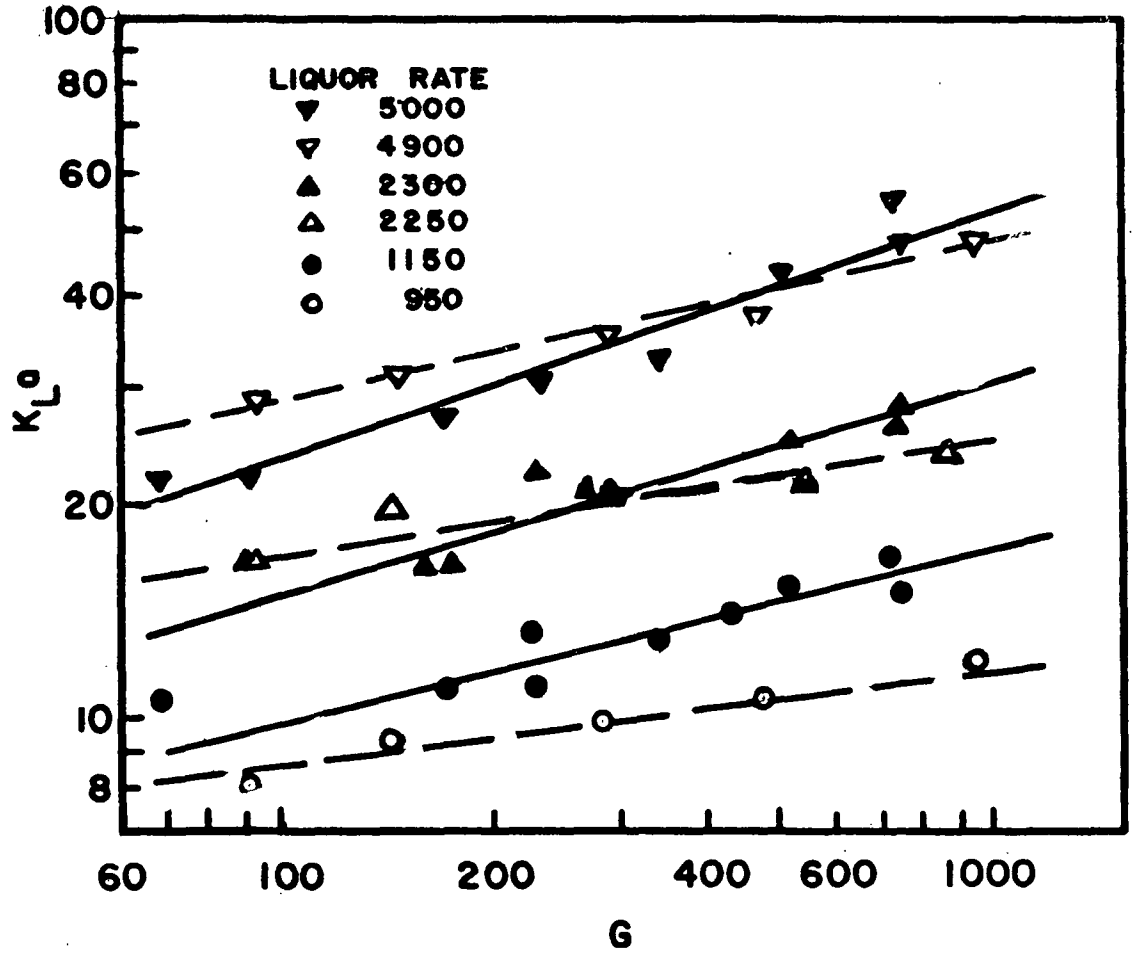


Figure 24. Comparison of Over—All Coefficients at High Gas Concentration with Those at Low Concentration.

Open data points are for high-concentration gas; closed are for low.

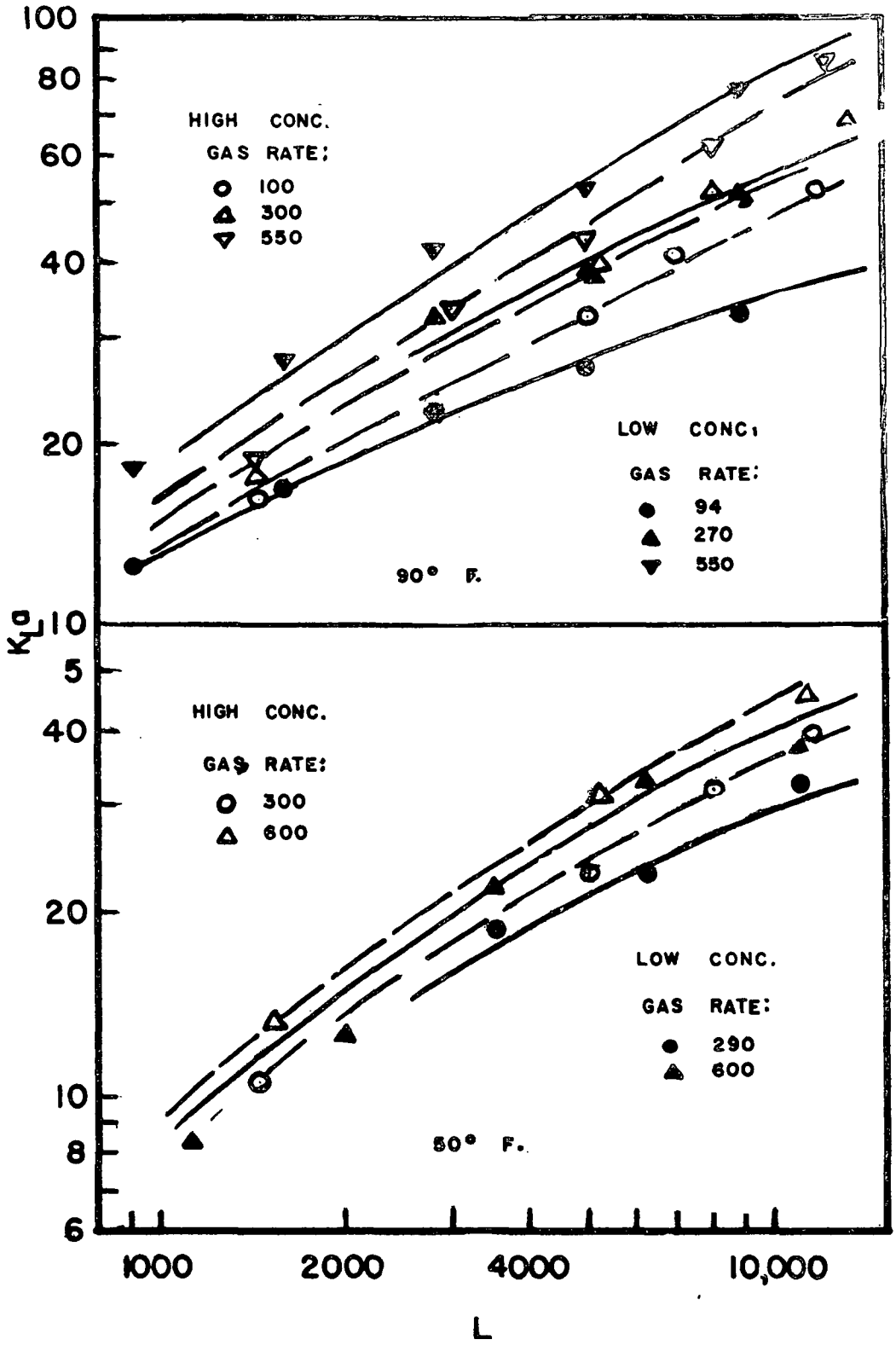


Figure 25. Over— All Absorption Coefficients for Low—Concentration Gases Compared with Those of Whitney and Vivian (7)

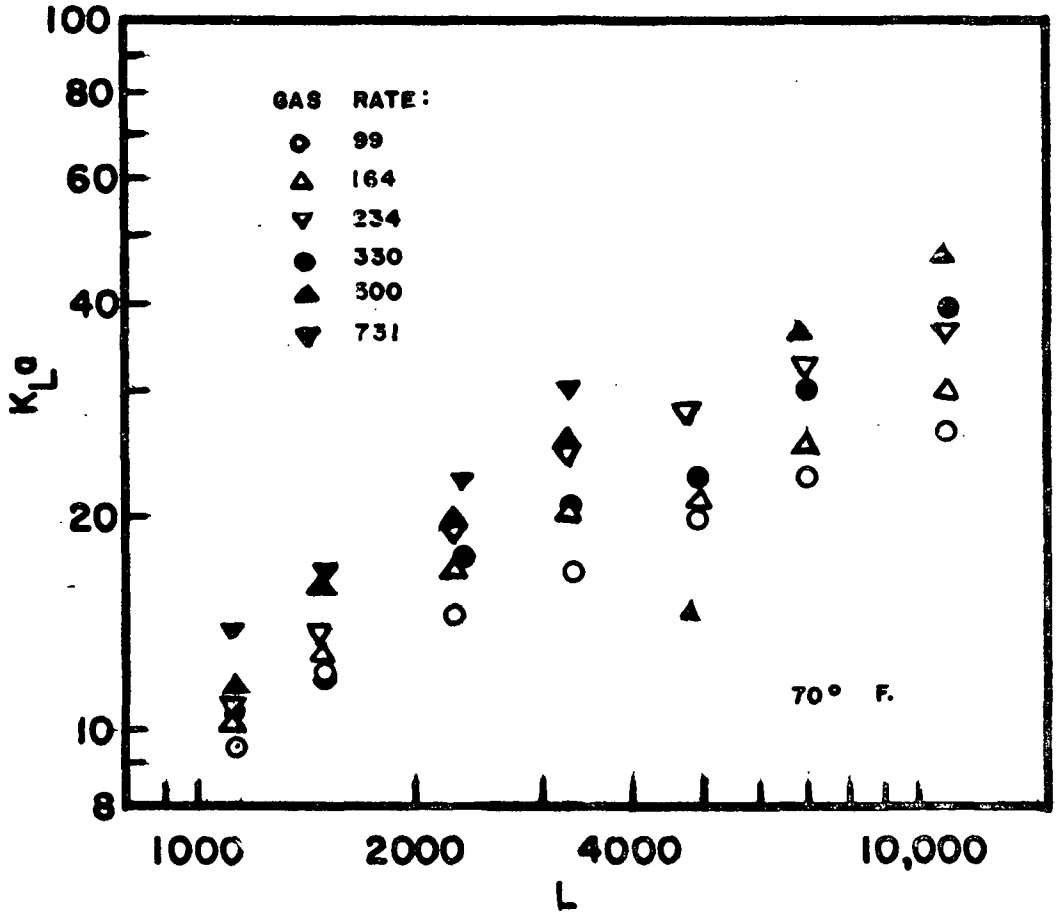


Figure 26. Over—All Absorption Coefficients for Low—Concentration Sulfur Dioxide Gases into 0.0580 Molal H_2SO_4 of 70°F.

TABLE XII

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 50°F.

Run No.	398	397	396	391	392	393	394	395
L, lb./hr. ft.^{2}	3500	6200	11,000	1130	2000	3500	6200	11,000
c_1, lb.-mol./ft.^{3}	0.000652	0.000476	0.000300	0.00158	0.00104	0.000887	0.000717	0.000540
G, lb./hr. ft.^{2}	292	292	292	603	605	605	608	530
p_1, atm. x 10^2	0.837	0.842	0.818	1.14	0.834	0.916	0.886	0.909
p_2, atm. x 10^2	0.496	0.922	0.263	1.07	0.718	0.699	0.569	0.352
$(K_L a)_n$	17.9	23.2	28.3	8.45	12.6	22.0	33.0	37.4
$k_G a$	9.50	11.5	12.5	10.6	14.7	19.3	23.2	26.1
H'	0.237	0.227	0.227	0.199	0.220	0.216	0.222	0.227
$(k_L a)_n$	31.2	42.9	84.6	10.1	15.5	29.2	48.3	55.2

TABLE XIII

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 90°F.

Run No.	409	410	411	412	413	406	405	407
$\underline{L}$, lb./hr.ft.^{2}	1130	2000	3500	6200	11,000	3500	6200	6200
$\underline{c}_1$, lb.-mol./ft.^{3}	0.000997	0.000531	0.000443	0.000270	0.000184	0.000706	0.000437	0.000400
$\underline{G}$, lb./hr. ft.^{2}	94.5	94.5	94.5	94.5	94.5	274	273	274
$\underline{p}_1$, atm. x 10^2	1.62	1.08	1.21	1.19	1.37	1.08	1.10	0.979
$\underline{p}_2$, atm. x 10^2	1.17	0.606	0.543	0.359	0.249	0.999	0.670	0.606
$(\underline{K}_L\underline{a})_n$	12.5	16.8	22.4	26.1	32.8	34.2	44.5	38.2
$\underline{k}_G\underline{a}$	3.24	4.07	4.88	5.69	6.34	9.95	11.0	11.0
$\underline{H}'$	0.0940	0.105	0.104	0.109	0.111	0.100	0.103	0.107
$(\underline{k}_L\underline{a})_n$	19.6	29.7	42.9	54.4	77.0	34.2	60.5	60.5

TABLE XIII (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION RUNS MADE AT 90°F.

Run No.	404	408	399	400	401	402	403
$\underline{L}$, lb./hr. ft.^{2}	11,000	11,000	1130	2000	3500	6200	11,000
$\underline{c}_1$, lb.-mol./ft.^{3}	0.000294	0.000331	0.000633	0.000608	0.000736	0.000553	0.000427
$\underline{G}$, lb./hr. ft.^{2}	273	268	546	546	546	546	495
$\underline{p}_1$, atm. x 10^2	1.06	1.19	0.594	0.668	1.16	1.01	1.05
$\underline{p}_2$, atm. x 10^2	0.401	0.501	0.557	0.597	0.944	0.737	0.481
$(\underline{K}_L\underline{a})_n$	51.5	51.8	18.1	27.6	37.0	52.5	77.5
$\underline{k}_G\underline{a}$	12.1	12.0	10.1	14.1	18.4	22.3	25.6
$\underline{H}'$	0.107	0.105	0.121	0.115	0.100	0.103	0.107
$(\underline{k}_L\underline{a})_n$	97.0	88.5	23.2	35.7	46.3	69.0	115

E. THE ABSORPTION OF LOW-CONCENTRATION SULFUR DIOXIDE INTO 0.0580 MOLAL SULFURIC ACID

The results for the absorption of sulfur dioxide of low concentration into 0.0580 molal sulfuric acid are shown in Figure 26 and are tabulated in Table XIV. The data exhibit too much variance to permit plotting as gas rate functions for constant liquor rate as was done for the water data in Figure 22, so the data are presented only as a function of liquor rate. The data reveal that the over-all coefficient for the hydrolysis-suppressed system is lower than for water in all cases, although the difference between the two systems is less at low liquor rates than at high.

F. ANALYSIS OF OVER-ALL COEFFICIENTS

1. HIGH-CONCENTRATION SULFUR DIOXIDE-WATER ABSORPTION DATA

Comparison of absorption data between different conditions and systems can properly be done only on the basis of individual film coefficients. Because $\underline{H}'$ values were not constant for any series of runs at low concentrations, the method of Wilson (6) would not seem to be applicable for the data of this thesis.

The method adopted is that of computing $\underline{k}_G\underline{a}$ and thereby $\underline{H}'/\underline{k}_G\underline{a}$, and by means of the additivity principle of Equation (8), subtracting

TABLE XIV

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE 0.0580 MOLAL SULFURIC ACID ABSORPTION

RUNS MADE AT 70°F.

Run No.	384	363	370	377	349	356	385	364	371	378
L, lb./hr.ft.^{2}	1130	1130	1130	1130	1130	1130	1500	1500	1500	1500
c_1, lb.-mol./ft.^{3}	0.000754	0.000756	0.000644	0.000722	0.000520	0.000881	0.000680	0.000805	0.000612	0.000499
G, lb./hr.ft.^{2}	99	161	234	345	500	731	99	164	234	345
p_1, atm. x 10^2	1.63	1.44	1.15	1.30	0.905	1.37	1.52	1.64	1.15	1.04
p_2, atm. x 10^2	1.49	1.25	1.06	1.24	0.859	1.30	1.20	1.40	1.03	0.980
$(K_L a)_n$	8.56	10.4	10.9	10.7	11.6	13.8	12.0	12.9	13.8	11.6
$(K_L a)_p$	11.1	13.5	13.1	13.8	14.4	15.6	15.5	16.7	19.2	15.2
$k_G a$	3.62	4.58	5.71	7.07	9.34	13.3	4.06	5.20	6.51	8.10
H'	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113
$(k_L a)_n$	11.6	14.0	14.1	15.8	13.5	15.6	18.0	17.9	18.2	13.8
$(k_L a)_p$	15.2	18.2	18.0	13.3	16.6	17.4	23.2	18.9	25.9	18.2

TABLE XIV (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE 0.0580 MOLAL SULFURIC ACID ABSORPTION

RUNS MADE AT 70°F.

Run No.	350	357	386	365	372	379	351	358	387	366
L, lb./hr.ft.^{2}	1490	1500	2280	2280	2330	2530	2280	2340	3520	3300
c_1, lb.-mol./ft.^{3}	0.000488	0.000778	0.000527	0.000754	0.000500	0.000439	0.000412	0.000551	0.000356	0.000592
G, lb./hr.ft.^{2}	485	700	99	164	234	345	500	731	99	164
p_1, atm. x 10^2	0.821	1.24	1.50	1.78	1.05	0.982	0.857	0.990	1.29	1.68
p_2, atm. x 10^2	0.780	1.19	1.04	1.40	0.841	0.858	0.762	0.916	0.815	1.23
$(K_L a)_n$	16.0	16.6	14.5	16.9	19.9	17.4	20.0	22.5	16.6	20.4
$(K_L a)_p$	19.5	22.4	18.9	22.0	26.8	22.4	23.9	29.1	21.0	26.1
$k_G a$	10.9	15.9	4.75	6.10	7.80	9.80	12.1	20.8	5.35	6.88
H'	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113
$(k_L a)_n$	19.5	18.8	22.2	24.6	27.9	20.8	24.6	25.6	25.6	30.6
$(k_L a)_p$	23.1	25.6	29.8	32.1	38.2	28.0	28.8	32.2	32.0	39.0

TABLE XIV (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE 0.0580 MOLAL SULFURIC ACID ABSORPTION

RUNS MADE AT 70°F.

Run No.	373	380	352	359	388	367	374	381	353	389
L, lb./hr.ft.^{2}	3300	3300	3300	3300	4950	4940	4950	4950	4950	7000
c_1, lb.-mol./ft.^{3}	0.000417	0.000424	0.000345	0.000463	0.000309	0.000428	0.000417	0.000349	0.000244	0.000232
G, lb./hr.ft.^{2}	234	345	500	731	99	164	234	345	532	99
p_1, atm. x 10^2	1.03	1.08	0.802	0.869	1.45	1.78	1.03	1.14	1.44	1.38
p_2, atm. x 10^2	0.722	0.960	0.707	0.783	0.742	1.07	0.722	1.07	1.22	0.581
$(K_L a)_n$	24.6	20.8	25.7	30.4	19.8	21.2	28.0	22.5	14.8	22.9
$(K_L a)_p$	31.8	26.9	30.3	39.2	25.6	27.3	36.1	29.0	15.8	29.5
$k_G a$	8.75	11.1	15.8	24.9	6.04	7.81	9.82	12.1	--	6.50
H'	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113	0.113
$(k_L a)_n$	36.1	26.4	31.5	38.9	31.4	36.0	41.3	28.4	--	38.2
$(k_L a)_p$	46.6	34.1	36.4	43.2	40.8	41.5	53.2	36.6	--	48.7

TABLE XIV (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE 0.0580 MOLAL SULFURIC ACID ABSORPTION

RUNS MADE AT 70°F.

Run No.	368	375	382	354	361	390
$\underline{L}$, lb./hr.ft.^{2}	7000	7000	7000	6990	7000	11,000
$\underline{c}_1$, lb.-mol./ft.^{3}	0.000332	0.000313	0.000307	0.000200	0.000283	0.000156
$\underline{G}$, lb./hr.ft.^{2}	161	234	345	532	680	99
$\underline{p}_1$, atm. x 10^2	1.60	1.21	1.16	0.720	0.952	1.39
$\underline{p}_2$, atm. x 10^2	0.960	0.735	0.870	0.534	0.887	0.491
$(\underline{K}_L\underline{a})_n$	25.2	32.4	30.1	36.7	30.8	26.4
$(\underline{K}_L\underline{a})_p$	32.6	41.9	38.9	41.6	39.8	33.8
$\underline{k}_G\underline{a}$	8.48	10.5	13.6	19.8	33.8	7.06
$\underline{H}'$	0.113	0.113	0.113	0.113	0.113	0.113
$(\underline{k}_L\underline{a})_n$	37.8	50.0	40.2	47.5	34.4	45.9
$(\underline{k}_L\underline{a})_p$	49.0	64.5	51.8	51.0	44.4	58.1

TABLE XIV (Continued)

SUMMARY OF LOW-CONCENTRATION SULFUR DIOXIDE 0.0580 MOLAL SULFURIC ACID ABSORPTION

RUNS MADE AT 70°F.

Run No.	369	376	383	355	362
$\underline{L}$, lb./hr.ft.^{2}	11,000	11,000	11,000	11,000	11,000
$\underline{c}_1$, lb.-mol./ft.^{3}	0.000242	0.000228	0.000235	0.000121	0.000185
$\underline{G}$, lb./hr.ft.^{2}	149	234	345	500	600
$\underline{p}_1$, atm. x 10^2	1.67	1.23	1.12	0.552	1.19
$\underline{p}_2$, atm. x 10^2	0.745	0.664	0.707	0.357	0.774
$(\underline{K}_L\underline{a})_n$	30.1	36.6	39.7	47.8	28.2
$(\underline{K}_L\underline{a})_p$	38.7	47.5	49.0	53.2	36.2
$\underline{k}_G\underline{a}$	9.27	11.3	14.8	21.8	31.6
$\underline{H}'$	0.113	0.113	0.113	0.113	0.113
$(\underline{k}_L\underline{a})_n$	47.6	57.5	56.8	63.6	31.0
$(\underline{k}_L\underline{a})_p$	61.0	75.1	69.0	67.5	39.8

$H'/k_G a$ from $1/K_L a$ to obtain the value of $k_L a$. In this manner $k_L a$ values were obtained which can be compared between systems and also within values predicted from oxygen desorption data.

Values of $k_G a$ were obtained by combining the values of $k_G a$ for the system ammonia-water obtained by Fellinger (16) with the values of k_G obtained by Taecker and Hougen (12) from vaporization studies with porous rings. The value of a, the effective interfacial area in square feet per cubic foot of packing, was thus obtained as a function of gas and liquor flow rate. The correlation of Taecker and Hougen for 1-inch ceramic Raschig rings is

$$k_G = 1.070 \, G/M_{p_{BM}} [\mu/D_G \rho]^{2/3} [G\sqrt{A_p}/\mu]^{0.41} \quad (31)$$

The correlation is based on the combination of the Schmidt number $[\mu/D_G \rho]$ and a modified Reynolds number $[G\sqrt{A_p}/\mu]$ where the term A_p is an area factor and represents the area in square feet of one piece of tower packing. The values in Equation (31) are the "mean film values" in each case. The diffusivity value D_G for the sulfur dioxide is for diffusion through air and was taken from a table appearing in Sherwood and Pigford's text (3) corrected for temperature by means of the Stoke-Einstein equation.

Physical liquid-film data for sulfur dioxide-water were computed from the correlation of Sherwood and Holloway corrected for the values

of oxygen desorption determined in this thesis and by the difference in diffusivity between sulfur dioxide and oxygen. The diffusivity values for sulfur dioxide through water and dilute sulfuric acid, Table XV, are those given by Peaceman (47) and represent the latest and most extensive data available.

TABLE XV

THE DIFFUSIVITY OF SULFUR DIOXIDE THROUGH WATER AND DILUTE (0.14-0.16 MOLAR) SULFURIC ACID FROM THE DATA OF PEACEMAN (47)

	Diffusivity, D_L, ft.^{2}/hr.			
	Water		Acid	
Temperature, °F.	Literature	Calc'd.	Literature	Calc'd.
50	---	4.33		
70	6.33	---	---	5.99
86			7.56	---
90	---	8.02		

Figure 27 shows the plot of individual film coefficients given in Table X for the high-concentration sulfur dioxide runs. It is seen that the normal and pseudocoefficients are not greatly separated and that the normal coefficients offer the better agreement with the predicted values. This result is contrary to that found by Whitney and Vivian (7) who report good agreement between the pseudocoefficients and the predicted line.

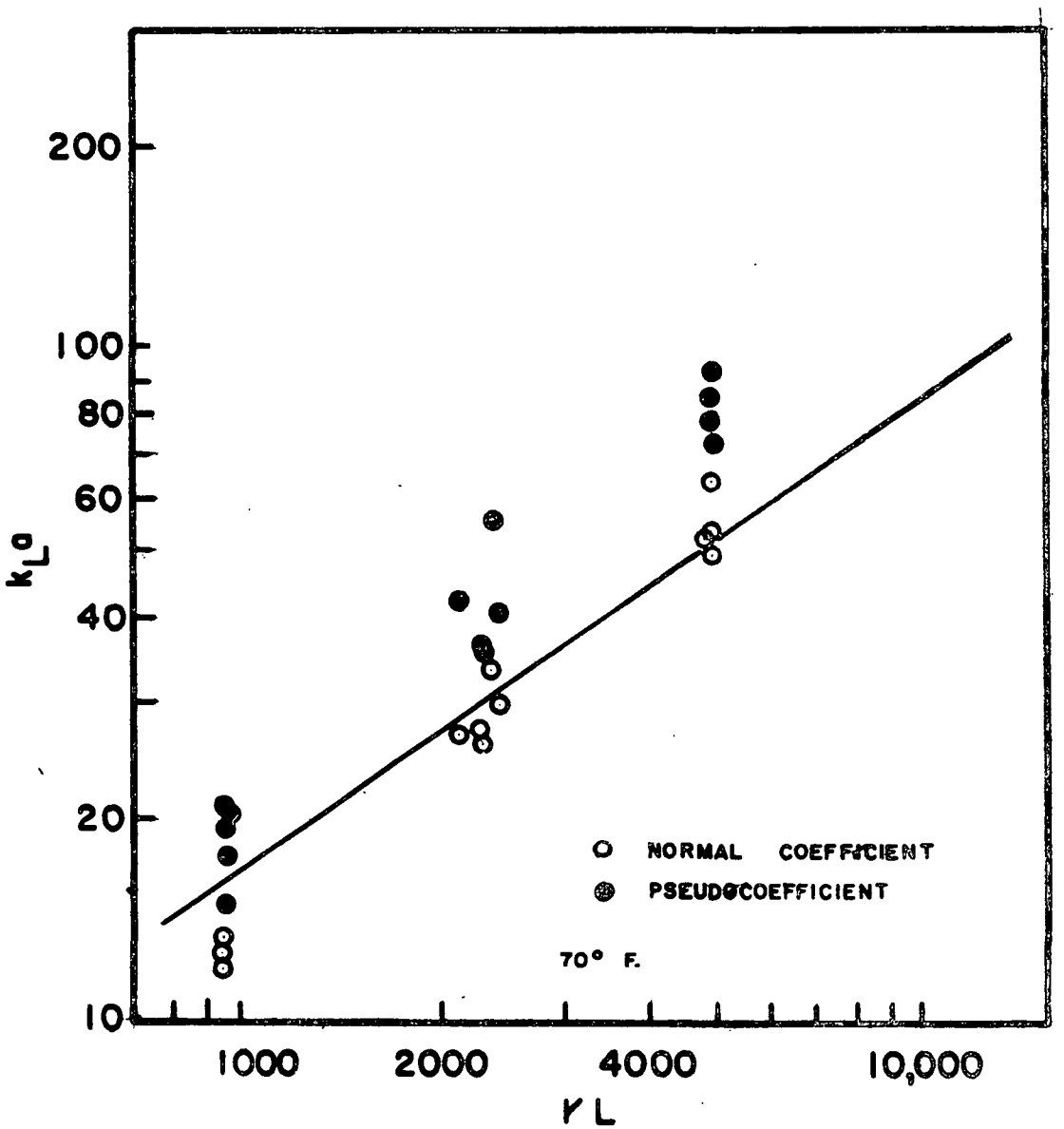


Figure 27. Individual Liquid—Film Coefficients for the Absorption of High—Contration Sulfur Dioxide into Water at 70° F. The line is the oxygen desorption line corrected for the diffusivity of SO_2.

The explanation of this disagreement may lie in the difference in the values of the over-all coefficients pointed out previously in connection with Figure 22, since the values of $\underline{k}_G \underline{a}$ do not differ greatly between the two investigations as is shown in Table XVI. Whitney and Vivian analyzed their over-all coefficients by use of the Wilson's graphical intercept method (6) referred to as method 5 of Table I (page 16). They obtained a correlation for $\underline{k}_G \underline{a}$ which is

$$\underline{k}_G \underline{a} = 0.0278\, \underline{G}^{0.7}\, \underline{L}^{0.25} \qquad (32)$$

TABLE XVI

COMPARISON OF THE VALUES OF $\underline{k}_G \underline{a}$ OBTAINED FROM THE CORRELATION OF TAECKER AND HOUGEN (12) IN CONJUNCTION WITH THE DATA OF FELLINGER (16) WITH THOSE FROM THE CORRELATION OF WHITNEY AND VIVIAN (7)

	Values from this thesis			Calc'd. from Whitney and Vivian
Run No.	$\underline{G}$	$\underline{L}$	$\underline{k}_G \underline{a}$	$\underline{k}_G \underline{a}$
60	94.2	2110	4.82	4.53
61	140	2340	5.72	6.14
62	288	2400	9.00	10.3
63	541	2260	15.0	15.7
64	851	2240	27.4	21.6

The agreement between values of $\underline{k}_G \underline{a}$ appear to be rather good.

2. LOW-CONCENTRATION SULFUR DIOXIDE ABSORPTION DATA

The over-all coefficients for absorption of low-concentration gases were analyzed in the same manner at those for the higher concentrations. The results obtained at 70°F. are shown in Figure 28 and for 50 and 90°F. in Figure 29. The data are tabulated in Tables XI, XII, and XIII respectively.

At 70° the normal liquid-film data give good agreement with the predicted line and the pseudo data are displaced to a considerable extent. This result indicated that the proper film coefficient is the normal one and thus supports the contention that reaction rate is infinite compared to rate of diffusion. The normal coefficients at 50 and 90°F. also show reasonably good agreement with the predicted data for these temperatures.

Figure 30 presents the plot of individual data for low-concentration sulfur dioxide absorption into dilute sulfuric acid (Table XIV). For this case the values for the normal and the pseudocoefficients approach each other much more closely than for the case of the water system. However, the pseudocoefficients give the better agreement with the predicted values. This result may be due to the fact that the true diffusivity values differ from those used or the presence of acid may actually affect the kinetics of the absorption process. Whatever the explanation may be, it appears that for the case of greater hydrolysis suppression, the two coefficients should approach each other much more closely.

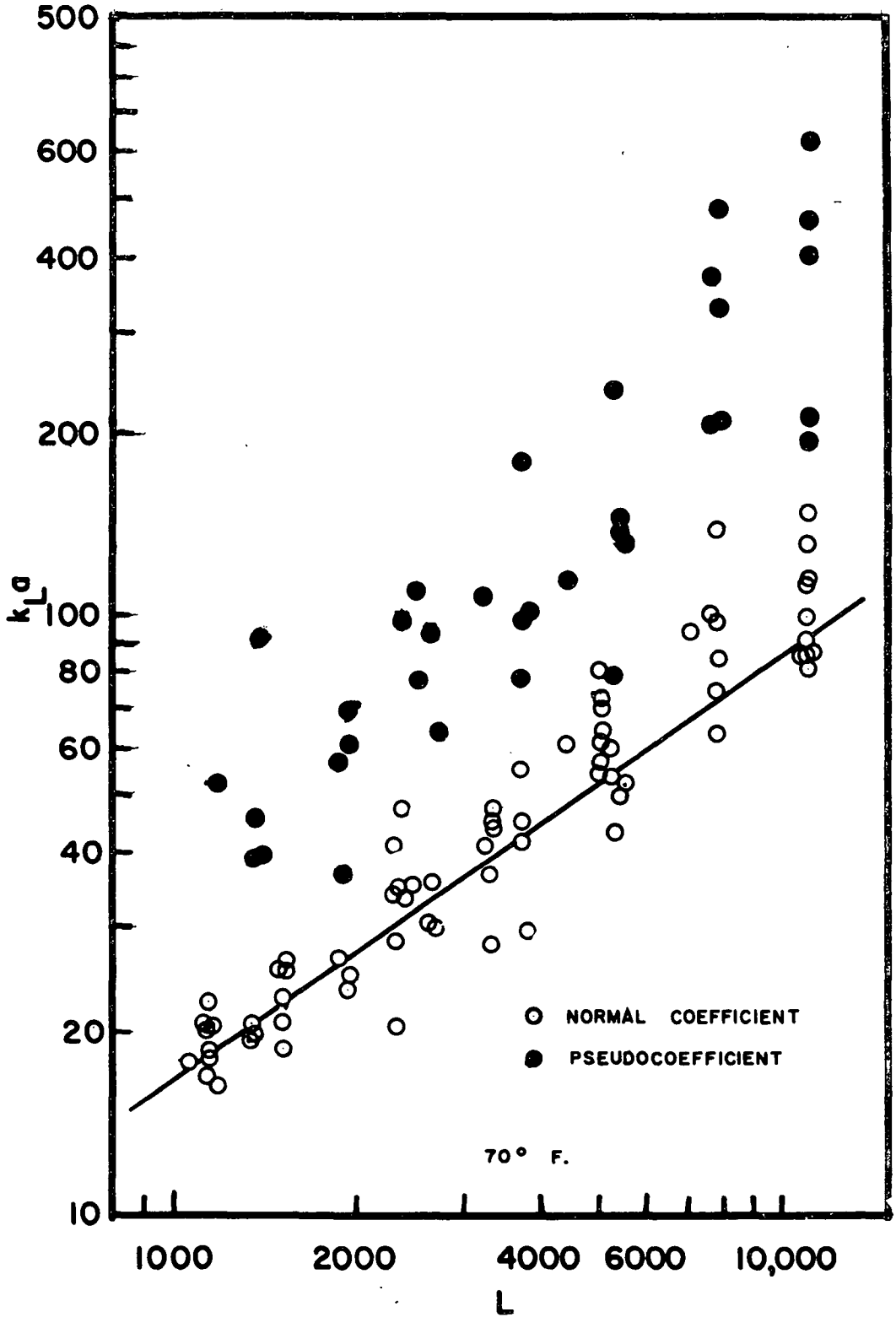


Figure 28. Individual Liquid — Film Coefficients for the Absorption of Low — Concentration Sulfur Dioxide into Water at 70° F.

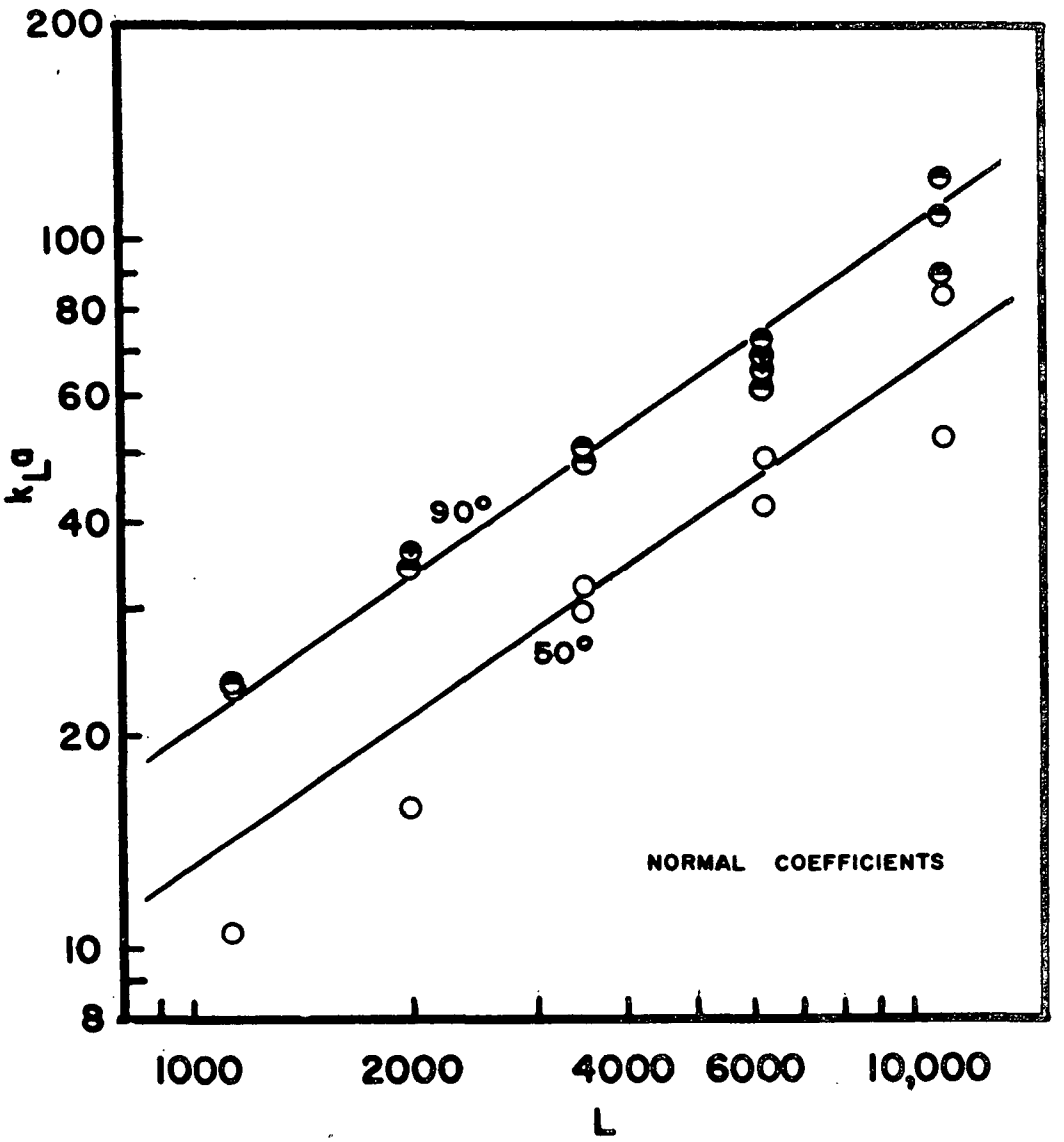


Figure 29. Individual Liquid Film Coefficients for the Absorption of Low-Concentration Sulfur Dioxide into Water at 50 and 90°F. The lines are the oxygen desorption lines for the designated temperatures corrected for the diffusivity of sulfur dioxide.

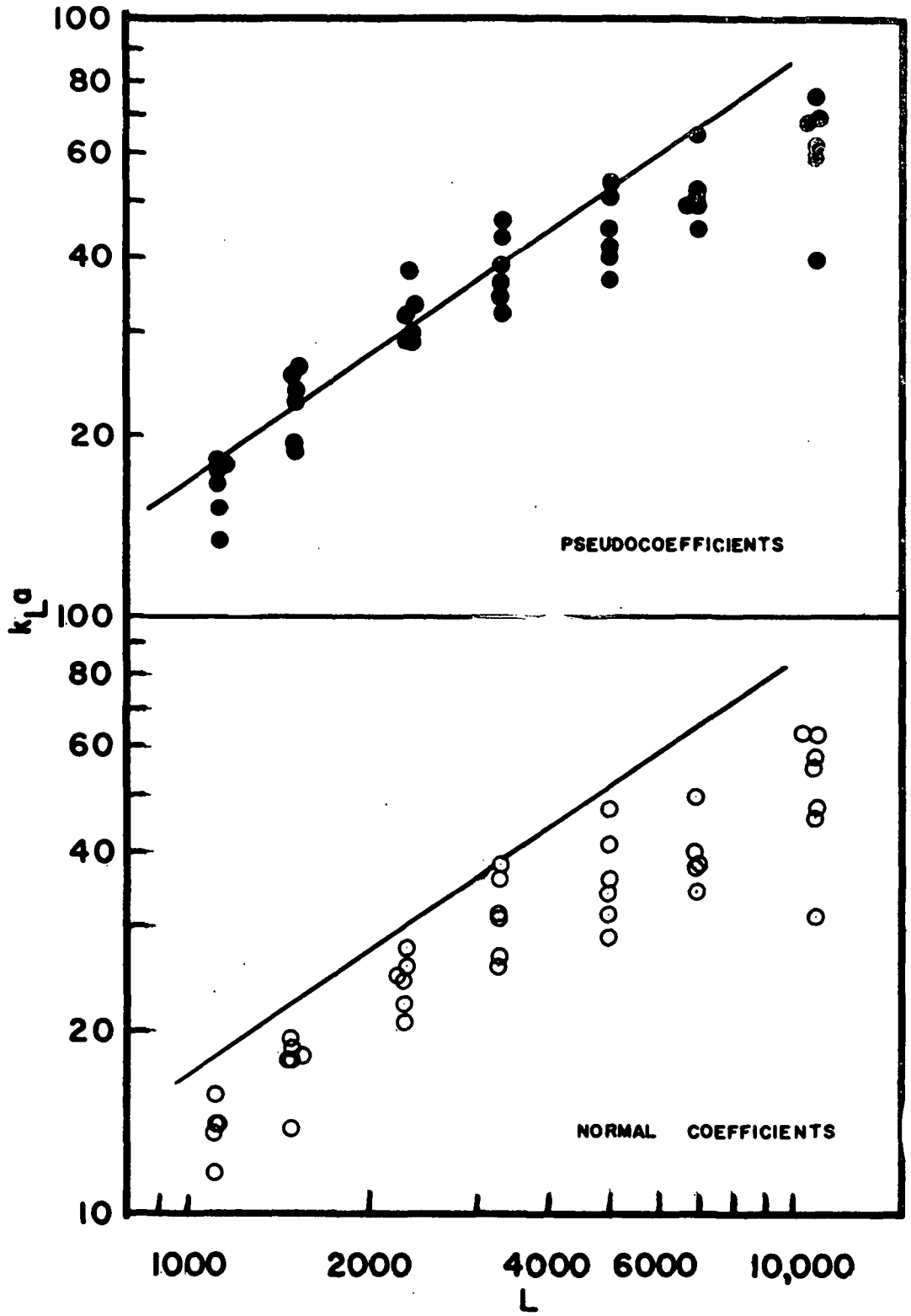


Figure 30. Individual Liquid – Film Coefficients for the Absorption of Low – Concentration Sulfur Dioxide into 0.0580 Molal Sulfuric Acid at 70° F.
The line is the oxygen desorption line corrected for the diffusivity of SO_2.

VII. SUMMARY AND CONCLUSIONS

1. The solubility of sulfur dioxide in water at partial pressures below 0.04 atmospheres has been determined for temperatures of 50, 60, 70, and 90°F.

2. The solubility of sulfur dioxide in 0.0580 molal sulfuric acid at partial pressures below 0.04 atmospheres has been determined at temperatures of 50, 70, and 90°F. Solubility determinations have also been made for 0.0580 molal sodium bisulfite and ammonium bisulfite solutions at 70°F. at partial pressures below 0.04 atmospheres.

3. The practicality of ultraviolet absorption as a method of analysis for sulfur dioxide gases of low concentration (0.030 - 1.50%) has been demonstrated.

4. Over-all absorption coefficients for the absorption of low-concentration sulfur dioxide into water have been obtained at 70°F.

5. The over-all absorption coefficients for low-concentration gases are smaller than corresponding coefficients for high-concentration gases. The difference is greater at low gas rates than at high.

6. If the individual liquid-film coefficient is assumed to be independent of solute concentration level, the variation in over-all coefficient can be attributed to the change in modified Henry's law coefficient in accordance with the two-film theory.

7. The over-all coefficients for the absorption of low-concentration gases into dilute sulfuric acid are lower than for absorption into water.

8. The precision of the data is not sufficient to warrant quantitative conclusions regarding the effect of hydrolysis suppression on the individual liquid-film coefficients.

9. It is recommended that the normal liquid-film coefficient be used for the design of industrial absorption equipment.

APPENDIX I

TABLE XVII

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	89	90	91	92	93
Temperature, °F.	80	80	80	80	80
Packed Height, ft.	2	2	2	2	2
Phase Flow Rates:					
L, lb./hr.ft.^{2}	3290	3290	3290	3290	3290
G, lb./hr.ft.^{2}	36.5	55.1	66.1	84.0	112
Temperatures:					
Liquid, inlet, °F.	80.0	80.0	80.0	80.0	80.0
outlet, °F.	80.0	80.0	80.0	80.0	80.0
Gas, feed, °F.	82.0	83.0	85.0	78.0	78.0
exit, °F.	80.0	80.0	80.0	80.0	80.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x 10^5/ft.^{3}	1.86	1.88	1.91	1.90	1.92
c_2, inlet, lb.-mol x 10^5/ft.^{3}	3.86	4.00	4.10	4.50	4.48
c_e, lb.-mol x 10^5/ft.^{3}	1.52	1.52	1.52	1.53	1.56
Driving Forces:					
$c_1 - c_e$, lb.-mol x 10^5/ft.^{3}	0.34	0.36	0.39	0.37	0.37
$c_2 - c_e$, lb.-mol x 10^5/ft.^{3}	2.34	2.48	2.58	2.97	2.92
$\log_e \Delta c_2/\Delta c_1$	1.93	1.93	1.90	2.08	2.07
Desorption Coefficient:					
$K_L ah$, ft./hr.	102	102	101	110	109
$K_L a$, hr.$^{-1}$	48.8	48.6	48.1	52.4	51.9

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	94	95	96	97	98
Temperature, °F.	80	80	80	80	80
Packed Height, ft.	2	2	2	2	2
Phase Flow Rates:					
L, lb./hr.ft.^{2}	3090	3090	3090	3090	3090
G, lb./hr.ft.^{2}	187	205	241	317	349
Temperatures:					
Liquid, inlet, °F.	80.0	79.0	80.0	80.0	80.0
outlet, °F.	80.0	79.0	80.0	80.0	80.0
Gas, feed, °F.	78.0	78.0	75.0	82.0	80.0
exit, °F.	80.0	79.0	80.0	80.0	80.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	1.95	1.96	1.99	1.99	1.98
c_2, inlet, lb.-mol x10^5/ft.^{3}	4.67	4.81	5.20	5.40	5.21
c_e, lb.-mol x10^5/ft.^{3}	1.53	1.54	1.53	1.54	1.54
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.42	0.42	0.46	0.45	0.44
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	3.14	3.27	3.67	3.86	3.67
$\log_e \Delta c_2 / \Delta c_1$	2.01	2.06	2.08	2.15	2.12
Desorption Coefficient:					
$K_L a$, ft./hr.	106	109	110	114	112
$K_L a$, hr.$^{-1}$	50.5	51.9	52.4	54.3	53.4

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	99	100	101	102	113
Temperature, °F.	80	80	80	80	70
Packed Height, ft.	2	2	2	2	2
Phase Flow Rates:					
L, lb./hr.ft.^{2}	3000	3000	3000	3000	1030
G, lb./hr.ft.^{2}	408	508	604	771	390
Temperatures:					
Liquid, inlet, °F.	80.0	80.0	80.0	80.0	70.3
outlet, °F.	80.0	79.5	80.0	80.0	70.0
Gas, feed, °F.	80.0	80.0	80.0	80.0	70.8
exit, °F.	80.0	78.0	80.0	80.0	70.4
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	1.99	1.94	1.89	1.81	1.89
c_2, inlet, lb.-mol x10^5/ft.^{3}	5.26	4.76	4.39	4.32	4.66
c_e, lb.-mol x10^5/ft.^{3}	1.56	1.52	1.53	1.54	1.69
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.43	0.42	0.36	0.27	0.20
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	3.70	3.24	2.76	2.78	2.97
$\log_e \Delta c_2 / \Delta c_1$	2.15	2.04	2.04	2.33	2.69
Desorption Coefficient:					
$K_L a$, ft./hr.	114	108	108	123	44.4
$K_L a$, hr.$^{-1}$	54.3	50.5	50.5	57.5	20.8

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	115	116	117	118	119
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	2
Phase Flow Rates:					
L, lb./hr.ft.^{2}	1800	2080	3180	4060	5520
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	70.0	70.0	70.0	70.0	70.0
outlet, °F.	69.7	70.0	70.0	70.0	70.0
Gas, feed, °F.	68.0	72.0	70.0	70.0	70.0
exit, °F.	69.9	70.0	70.0	70.0	70.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	2.11	2.15	2.23	2.28	2.32
c_2, inlet, lb.-mol x10^5/ft.^{3}	5.60	5.74	5.34	5.13	5.08
c_e, lb.-mol x10^5/ft.^{3}	1.69	1.69	1.69	1.69	1.69
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.42	0.46	0.54	0.59	0.63
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	3.91	4.05	3.65	3.44	3.39
$\log_e \Delta c_2 / \Delta c_1$	2.23	2.18	1.91	1.76	1.68
Desorption Coefficient:					
$K_L a h$, ft./hr.	64.2	72.6	97.2	114	148
$K_L a$, hr.$^{-1}$	30.0	33.9	45.4	53.3	69.1

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	120	121	122	133	134
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	1	1
Phase Flow Rates:					
L, lb./hr.ft.^{2}	6920	9000	11,900	972	1410
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	70.0	70.0	70.0	70.1	70.0
outlet, °F.	70.0	70.0	70.0	70.0	69.9
Gas, feed, °F.	70.0	70.9	72.0	69.9	69.9
exit, °F.	70.0	70.0	70.0	70.0	70.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	2.38	2.50	2.59	1.98	2.08
c_2, inlet, lb.-mol x10^5/ft.^{3}	4.89	4.87	4.95	3.28	3.56
c_e, lb.-mol x10^5/ft.^{3}	1.69	1.69	1.69	1.71	1.71
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.69	0.81	0.90	0.27	0.37
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	3.20	3.18	3.26	1.57	1.85
$\log_e \Delta c_2 / \Delta c_1$	1.53	1.37	1.29	1.76	1.61
Desorption Coefficient:					
$K_L a$, ft./hr.	170	197	245	27.4	36.4
$K_L a$, hr.$^{-1}$	79.5	92.1	114	23.8	31.7

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	135	136	137	138	139
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
Phase Flow Rates:					
L, lb./hr.ft.^{2}	1810	2290	3130	4040	5400
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	70.0	70.0	70.0	70.0	70.0
outlet, °F.	70.0	70.0	70.0	70.0	70.0
Gas, feed, °F.	70.0	70.0	70.0	70.0	70.0
exit, °F.	70.0	70.0	70.0	70.0	70.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	2.15	2.29	2.43	2.51	2.57
c_2, inlet, lb.-mol x10^5/ft.^{3}	3.75	4.34	4.28	4.18	4.36
c_e, lb.-mol x10^5/ft.^{3}	1.71	1.71	1.71	1.71	1.71
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.44	0.58	0.72	0.80	0.86
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	2.04	2.63	2.57	2.47	2.65
$\log_e \Delta c_2 / \Delta c_1$	1.53	1.51	1.27	1.12	1.12
Desorption Coefficient:					
$K_L ah$, ft./hr.	44.4	55.3	63.6	72.4	96.8
$K_L a$, hr.$^{-1}$	38.6	48.1	55.4	62.9	84.2

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	140	141	142	169	170
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	2	2
Phase Flow Rates:					
L, lb./hr.ft.^{2}	6880	8800	11,600	1010	1010
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	70.0	70.0	70.0	69.5	70.0
outlet, °F.	70.0	70.0	70.0	69.5	70.1
Gas, feed, °F.	72.0	70.0	69.4	69.0	72.0
exit, °F.	70.0	70.0	70.0	69.5	70.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	2.68	2.80	3.03	1.91	1.95
c_2, inlet, lb.-mol x10^5/ft.^{3}	4.34	4.44	4.59	3.30	3.94
c_e, lb.-mol x10^5/ft.^{3}	1.71	1.71	1.71	1.72	1.71
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.97	1.09	1.32	0.19	0.24
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	2.63	2.73	2.88	1.58	2.23
$\log_e \Delta c_2 / \Delta c_1$	0.995	0.915	0.779	2.12	2.22
Desorption Coefficient:					
$K_L a$, ft./hr.	109	129	145	34.3	36.0
$K_L a$, hr.$^{-1}$	95.0	112	126	16.0	16.8

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	171	172	173	174	176
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	2
Phase Flow Rates:					
L, lb./hr.ft.^{2}	1820	1820	3240	3240	950
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	70.0	70.0	70.0	70.0	70.0
outlet, °F.	70.1	70.0	70.0	70.0	70.0
Gas, feed, °F.	72.0	70.0	69.0	70.0	70.0
exit, °F.	70.0	70.0	70.0	70.0	70.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	2.04	2.08	2.26	2.20	1.84
c_2, inlet, lb.-mol x10^5/ft.^{3}	4.56	4.82	5.33	4.82	2.61
c_e, lb.-mol x10^5/ft.^{3}	1.71	1.71	1.71	1.71	1.74
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.33	0.37	0.55	0.49	0.10
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	2.85	3.11	3.62	3.11	0.87
$\log_e \Delta c_2/\Delta c_1$	2.16	2.13	1.88	1.85	2.16
Desorption Coefficient:					
$K_L a h$, ft./hr.	63.0	62.2	97.8	96.2	33.0
$K_L a$, hr.$^{-1}$	29.4	29.0	45.7	44.9	15.4

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	177	178	179	180	181
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	2
Phase Flow Rates:					
L, lb./hr.ft.^{2}	3500	11,000	1100	1640	2470
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	70.0	70.0	70.0	70.2	70.1
outlet, °F.	70.0	70.0	70.0	70.3	70.0
Gas, feed, °F.	70.0	70.0	69.9	72.0	72.0
exit, °F.	70.0	70.0	69.0	70.2	70.2
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	1.96	2.08	2.04	2.07	2.12
c_2, inlet, lb.-mol x10^5/ft.^{3}	2.86	2.92	3.49	3.85	4.28
c_e, lb.-mol x10^5/ft.^{3}	1.74	1.74	1.71	1.70	1.71
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.22	0.34	0.334	0.365	0.406
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	1.12	3.46	1.78	2.15	2.58
$\log_e \Delta c_2 / \Delta c_1$	1.63	1.24	1.67	1.77	1.85
Desorption Coefficient:					
$K_L a$, ft./hr.	91.7	220	29.6	46.6	73.3
$K_L a$, hr.$^{-1}$	49.0	104	13.8	21.8	34.2

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	182	183	184	185	186
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	2
Phase Flow Rates:					
L, lb./hr.ft.^{2}	3000	3750	4900	7220	9200
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	70.2	70.0	70.0	70.0	70.0
outlet, °F.	70.0	70.0	70.1	70.0	70.1
Gas, feed, °F.	70.0	70.0	71.0	70.0	70.5
exit, °F.	70.1	70.0	70.0	70.0	70.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	2.25	2.30	2.34	2.42	2.48
c_2, inlet, lb.-mol x10^5/ft.^{3}	4.38	4.44	4.46	4.40	4.48
c_e, lb.-mol x10^5/ft.^{3}	1.71	1.71	1.71	1.71	1.71
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.542	0.592	0.628	0.710	0.770
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	2.67	2.73	2.75	2.73	2.77
$\log_e \Delta c_2 / \Delta c_1$	1.60	1.53	1.48	1.35	1.28
Desorption Coefficient:					
$K_L ah$, ft./hr.	76.9	92.0	116	156	189
$K_L a$, hr.$^{-1}$	35.9	43.0	54.3	72.9	88.4

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	187	188	189	190	191
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	1	1	1
Phase Flow Rates:					
L, lb./hr.ft.^{2}	10,800	3250	1120	1270	1640
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	70.0	70.0	70.0	70.1	70.4
outlet, °F.	70.1	69.9	70.0	70.0	70.1
Gas, feed, °F.	70.5	68.0	70.5	72.0	70.0
exit, °F.	70.0	70.0	69.5	70.0	70.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	2.56	2.25	1.94	1.99	2.03
c_2, inlet, lb.-mol x10^5/ft.^{3}	4.52	4.66	2.64	2.73	2.89
c_e, lb.-mol x10^5/ft.^{3}	1.71	1.71	1.71	1.71	
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.854	0.536	0.228	0.278	1.19
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	2.82	2.95	0.930	1.02	0.331
$\log_e \Delta c_2 / \Delta c_1$	1.19	1.70	1.41	1.30	1.28
Desorption Coefficient:					
$K_L a$, ft./hr.	207	87.3	25.3	26.7	33.7
$K_L a$, hr.$^{-1}$	96.6	40.8	22.0	23.2	29.3

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	192	193	194	195	196
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
Phase Flow Rates:					
L, lb./hr.ft.^{2}	2250	2900	3700	4900	7850
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	70.0	70.0	70.0	70.0	70.0
outlet, °F.	70.0	70.0	70.0	70.0	70.0
Gas, feed, °F.	70.2	71.0	70.0	70.0	70.0
exit, °F.	70.0	70.0	70.0	70.0	70.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	2.16	2.21	2.25	2.25	2.34
c_2, inlet, lb.-mol x10^5/ft.^{3}	3.18	3.16	3.33	3.21	3.17
c_e, lb.-mol x10^5/ft.^{3}					
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	1.47	1.45	1.62	1.50	0.626
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	0.450	0.496	0.544	0.544	1.46
$\log_e \Delta c_2 / \Delta c_1$	1.18	1.07	1.09	1.01	0.772
Desorption Coefficient:					
$K_L a$, ft./hr.	42.8	50.0	64.6	78.5	97.5
$K_L a$, hr.$^{-1}$	37.2	43.5	56.1	68.3	84.8

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	176	177	178	179	180
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	2
Phase Flow Rates:					
L, lb./hr.ft.^{2}	950	3500	11,000	1100	1640
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	71.0	71.0	71.0	70.0	70.2
outlet, °F.	--	--	--	70.0	70.3
Gas, feed, °F.	--	--	--	69.9	72.0
exit, °F.	--	--	--	69.0	70.2
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	1.84	1.96	2.08	2.044	2.068
c_2, inlet, lb.-mol x10^5/ft.^{3}	2.56	2.86	2.80	3.49	3.85
c_e, lb.-mol x10^5/ft.^{3}	1.74	1.74	1.74	1.71	1.70
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.10	0.22	0.34	0.33	0.36
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	0.82	0.98	1.06	1.78	2.15
$\log_e \Delta c_2 / \Delta c_1$	2.10	1.87	1.26	1.67	1.77
Desorption Coefficient:					
$K_L a$, ft./hr.	33.0	105	223	29.6	46.6
$K_L a$, hr.$^{-1}$	15.4	49.0	104	13.8	21.8

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	181	182	183	184	185
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	2
Phase Flow Rates:					
L, lb./hr.ft.^{2}	2470	3000	3750	4900	7220
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	70.1	70.2	70.0	70.0	70.0
outlet, °F.	70.0	70.0	70.0	70.1	70.0
Gas, feed, °F.	72.0	70.0	70.0	71.0	70.0
exit, °F.	70.2	70.1	70.0	70.0	70.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	2.12	2.25	2.30	2.34	2.42
c_2, inlet, lb.-mol x10^5/ft.^{3}	4.28	4.38	4.44	4.46	4.40
c_e, lb.-mol x10^5/ft.^{3}	1.71	1.71	1.71	1.71	1.71
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.41	0.54	0.59	0.63	0.71
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	2.58	2.67	2.73	2.75	2.73
$\log_e \Delta c_2 / \Delta c_1$	1.85	1.60	1.53	1.48	1.35
Desorption Coefficient:					
$K_L ah$, ft./hr.	73.3	76.9	92.0	116	156
$K_L a$, hr.$^{-1}$	34.2	35.9	43.0	54.3	72.9

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	186	187	188	189	190
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	1	1
Phase Flow Rates:					
L, lb./hr.ft.^{2}	9200	10,800	3250	1120	1270
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	70.0	70.0	70.0	70.0	70.1
outlet, °F.	70.1	70.1	69.9	70.0	70.0
Gas, feed, °F.	70.5	70.5	68.0	70.5	72.0
exit, °F.	70.0	70.0	70.0	69.5	70.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	4.48	4.52	4.66	1.94	1.99
c_2, inlet, lb.-mol x10^5/ft.^{3}	2.48	2.56	2.25	2.64	2.73
c_e, lb.-mol x10^5/ft.^{3}	1.71	1.71	1.71	1.71	1.71
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.77	0.85	0.54	0.23	0.28
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	2.78	2.82	2.95	0.93	1.02
$\log_e \Delta c_2 / \Delta c_1$	1.28	1.19	1.70	1.41	1.30
Desorption Coefficient:					
$K_L a$, ft./hr.	189	207	87.3	25.3	26.7
$K_L a$, hr.$^{-1}$	88.4	96.6	40.8	22.0	23.2

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	191	192	193	194	195
Temperatures, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
Phase Flow Rates:					
L, lb./hr.ft.^{2}	1640	2250	2900	3700	4900
G, lb./hr.ft.^{2}	390	390	390	390	390
Temperatures:					
Liquid, inlet, °F.	70.4	70.0	70.0	70.0	70.0
outlet, °F.	70.1	70.0	70.0	70.0	70.0
Gas, feed, °F.	70.0	70.2	71.0	70.0	70.0
exit, °F.	70.0	70.0	70.0	70.0	70.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	2.03	2.16	2.21	2.25	2.25
c_2, inlet, lb.-mol x10^5/ft.^{3}	2.89	3.18	3.16	3.33	3.21
c_e, lb.-mol x10^5/ft.^{3}	1.70	1.71	1.71	1.71	1.71
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.33	0.45	0.50	0.54	0.54
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	3.59	3.27	2.92	2.97	2.75
$\log_e \Delta c_2 / \Delta c_1$	1.28	1.18	1.07	1.09	1.01
Desorption Coefficient:					
$K_L a h$, ft./hr.	33.7	42.8	50.0	64.6	78.5
$K_L a$, hr.$^{-1}$	29.3	37.2	43.5	56.1	68.3

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	294	299	296	297	298
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
Phase Flow Rates:					
L, lb./hr.ft.^{2}	3714	2796	2091	1221	724
G, lb./hr.ft.^{2}	65	65	65	65	65
Temperatures:					
Liquid, inlet, °F.	70.0	70.0	70.0	70.3	70.3
outlet, °F.	70.0	70.0	70.0	70.5	70.6
Gas, feed, °F.	71.1	71.0	71.0	71.0	71.0
exit, °F.	70.0	70.0	70.3	70.6	70.2
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	3.11	2.96	2.85	2.51	2.41
c_2, inlet, lb.-mol x10^5/ft.^{3}	5.43	5.26	5.05	4.32	4.19
c_e, lb.-mol x10^5/ft.^{3}	1.69	1.69	1.69	1.69	1.69
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	1.42	1.27	1.16	0.82	0.72
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	3.74	3.57	3.36	2.63	2.50
$\log_e \Delta c_2/\Delta c_1$	0.968	1.04	1.07	1.17	1.25
Desorption Coefficient:					
$K_L ah$, ft./hr.	57.7	46.7	36.0	22.9	14.5
$K_L a$, hr.$^{-1}$	50.2	40.6	31.4	19.9	12.6

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	299	300	301	302	303
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	2
Phase Flow Rates:					
L, lb./hr.ft.^{2}	821	1258	1983	2269	2981
G, lb./hr.ft.^{2}	65	65	65	65	65
Temperatures:					
Liquid, inlet, °F.	70.4	70.0	70.0	70.0	70.0
outlet, °F.	70.6	70.1	70.5	70.2	70.2
Gas, feed, °F.	70.5	71.1	71.0	71.5	72.0
exit, °F.	70.4	70.0	70.2	70.0	70.0
Liquid Concentrations:					
c_1, outlet, lb.-mol x10^5/ft.^{3}	2.23	2.39	2.46	2.61	2.66
c_2, inlet, lb.-mol x10^5/ft.^{3}	6.15	6.08	5.76	6.66	6.66
c_e, lb.-mol x10^5/ft.^{3}	1.68	1.69	1.68	1.69	1.69
Driving Forces:					
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	0.55	0.70	0.77	0.92	0.98
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	4.47	4.39	4.07	4.97	4.98
$\log_e \Delta c_2/\Delta c_1$	2.09	1.83	1.66	1.69	1.63
Desorption Coefficient:					
$K_L ah$, ft./hr.	27.6	40.0	52.8	61.5	81.3
$K_L a$, hr.$^{-1}$	72.9	18.7	24.7	28.8	38.0

TABLE XVII (Continued)

SUMMARIZED DATA FOR THE DESORPTION OF OXYGEN FROM WATER IN AN 8-INCH TOWER PACKED WITH 1-INCH RASCHIG RINGS

Run No.	305	306	307	308
Temperature, °F.	70	70	70	70
Packed Height, ft.	2	2	2	2
Phase Flow Rates:				
L, lb./hr.ft.^{2}	5096	6120	8150	11,100
G, lb./hr.ft.^{2}	65	65	65	65
Temperatures:				
Liquid, inlet, °F.	70.0	70.0	70.0	70.0
outlet, °F.	70.0	70.1	70.0	70.0
Gas, feed, °F.	72.0	72.1	73.0	73.0
exit, °F.	70.0	70.0	70.0	70.0
Liquid Concentrations:				
c_1, outlet, lb.-mol x10^5/ft.^{3}	2.79	2.86	2.98	3.16
c_2, inlet, lb.-mol x10^5/ft.^{3}	6.49	6.58	6.23	6.13
c_e, lb.-mol x10^5/ft.^{3}	1.69	1.69	1.69	1.69
Driving Forces:				
$c_1 - c_e$, lb.-mol x10^5/ft.^{3}	1.11	1.18	1.29	1.47
$c_2 - c_e$, lb.-mol x10^5/ft.^{3}	4.80	4.90	4.54	4.44
$\log_e \Delta c_2 / \Delta c_1$	1.47	1.42	1.26	1.10
Desorption Coefficient:				
$K_L ah$, ft./hr.	120	140	165	196
$K_L a$, hr.$^{-1}$	56.0	65.3	77.0	91.5

TABLE XVIII

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF HIGH CONCENTRATION INTO WATER. SUMMARY OF DATA

Run No.	55	56	57	58	59
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	2
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	949	949	949	949	949
T_1, outlet, °F.	72.0	73.0	73.0	73.0	74.0
T_2, inlet, °F.	70.0	70.0	70.0	70.0	70.1
c_1, outlet, lb.-mol/ft.^{3}	0.00450	0.00564	0.00617	0.00740	0.0145
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr.ft.}^2}$	0.0686	0.0860	0.0940	0.113	0.244
Gas Side Measurements:					
G, lb./hr. ft.^{2}	87.5	144	284	470	942
G'_m, lb.-mol/hr.ft.^{2}	3.05	4.60	9.10	14.2	23.4
t_1, feed, °F.	83.0	83.3	77.0	77.0	75.2
t_2, exit, °F.	73.0	73.0	72.0	72.8	73.8
p_1, feed, atm.	0.0594	0.0661	0.0677	0.0786	0.167
p_2, exit, atm.	0.0317	0.0457	0.0555	0.0708	0.157
P, av. tower, atm.	0.987	1.01	0.983	1.00	0.991
Moles SO_2 lost $\frac{\text{lb.-mol}}{\text{hr.ft.}^2}$	0.0877	0.101	0.127	0.125	0.304
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.28	1.17	0.740	1.10	1.25
Over-all Coefficient:					
$K_L a$h, ft./hr. (corrected to 70°F)	17.5	20.1	21.3	22.8	26.0
$K_L a$, hr.$^{-1}$	8.17	9.30	9.95	10.7	12.1

TABLE XVIII (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF HIGH CONCENTRATION INTO WATER. SUMMARY OF DATA

Run No.	60	61	62	63	64
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	2
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	2110	2340	2400	2260	2240
T_1, outlet, °F.	72.0	72.0	72.5	73.0	73.0
T_2, inlet, °F.	70.0	70.0	70.1	70.0	70.1
c_1, outlet, lb.-mol/ft.^{3}	0.00720	0.00656	0.00770	0.00959	0.00992
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr.ft.}^2}$	0.244	0.249	0.296	0.346	0.359
Gas Side Measurements:					
G, lb./hr.ft.^{2}	94.2	140	288	541	851
G'_m, lb.-mol/hr.ft.^{2}	3.06	4.54	8.90	13.3	25.4
t_1, feed, °F.	75.2	78.8	75.9	76.8	73.9
t_2, exit, °F.	72.0	71.8	72.0	72.0	72.0
p_1, feed atm.	0.121	0.0974	0.101	0.120	0.118
p_2, exit atm.	0.0595	0.0537	0.0835	0.0968	0.103
P, av. tower, atm.	0.995	1.01	0.993	1.01	0.998
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr.ft.}^2}$	0.254	0.263	0.285	0.359	0.47
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.04	1.05	0.963	1.04	1.27
Over-all Coefficient:					
$K_L ah$, ft./hr.(corrected to 70°F.)	35.9	43.9	46.2	46.5	49.8
$K_L a$, hr.$^{-1}$	16.8	20.5	21.6	21.8	23.8

TABLE XVIII (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF HIGH CONCENTRATION INTO WATER. SUMMARY OF DATA

Run No.	65	66	67	68	69
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	2
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	4900	4870	4910	4900	4910
T_1, outlet, °F.	71.1	71.3	71.1	72.0	72.0
T_2, inlet, °F.	69.9	70.0	69.9	70.0	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.00540	0.00605	0.00512	0.00678	0.00625
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr.ft.}^2}$	0.425	0.487	0.405	0.540	0.493
Gas Side Measurements:					
G, lb./hr.ft.^{2}	86.9	141	282	465	931
G'_m, lb.-mol/hr.ft.^{2}	3.04	4.62	9.29	14.5	25.2
t_1, feed, °F.	73.0	78.8	73.0	83.0	76.5
t_2, exit, °F.	72.3	72.8	72.3	72.6	72.2
p_1, feed atm.	0.1406	0.1287	0.0808	0.0993	0.0753
p_2, exit atm.	0.0234	0.0396	0.0437	0.0666	0.0539
P, av. tower, atm.	0.989	1.01	0.988	1.00	0.994
Moles SO_2 lost $\frac{\text{lb.-mol}}{\text{hr.ft.}^2}$	0.407	0.471	0.399	0.551	0.630
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.958	0.967	0.985	1.02	1.28
Over-all Coefficient:					
$K_L a h$, ft./hr.(corrected to 70°F.)	61.5	68.4	76.6	80.5	104
$K_L a$, hr.$^{-1}$	28.8	31.9	35.8	37.6	48.7

TABLE XIX

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	198	199	200	201	202
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	11,000	7750	5200	3700	2470
T_1, outlet, °F.	70.2	70.0	69.8	70.2	69.5
T_2, inlet, °F.	70.0	70.0	69.5	70.2	69.5
c_1, outlet, lb.-mol/ft.^{3}	0.000629	0.000519	0.000335	0.000251	0.000148
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.111	0.0643	0.0280	0.0149	0.00588
Gas Side Measurements:					
G, lb./hr.ft.^{2}	272	272	272	272	272
G_m, lb.-mol/hr.ft.^{2}	9.43	9.43	9.43	9.43	9.43
t_1, feed, °F.	68.0	68.5	68.3	69.5	69.5
t_2, exit, °F.	70.0	70.0	69.6	70.2	69.3
p_1, feed, atm.x10^2	1.390	0.729	0.156	0.0811	0.0883
p_2, exit, atm. x10^2	0.592	0.241	0.0365	0.0176	0.0256
P, av. tower, atm.	0.980	0.980	0.980	0.980	0.980
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0807	0.0487	0.0118	0.00592	0.00647
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.726	0.757	0.420	0.400	1.10
Over-all Coefficient:					
$K_L a$, ft./hr.	70.8	76.5	21.0	28.0	52.0
$K_L a$, hr.$^{-1}$	61.6	66.5	18.3	24.4	45.3

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	203	208	209	210	211
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1870	1350	990	11,000	7750
T_1, outlet, °F.	69.5	70.0	70.2	70.0	70.0
T_2, inlet, °F.	70.1	70.1	70.2	70.1	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000477	0.00133	0.00187	0.000270	0.000331
Moles SO_2 absorbed, $\frac{\text{lb.-mol}_2}{\text{hr. ft.}}$	0.0143	0.0289	0.0297	0.0478	0.0410
Gas Side Measurements:					
G, lb./hr.ft.^{2}	272	272	272	272	272
G_m, lb.-mol/hr.ft.^{2}	9.43	9.43	9.43	9.43	9.43
t_1, feed, °F.	69.3	69.2	70.0	70.1	70.0
t_2, exit, °F.	70.0	70.0	70.0	70.0	70.0
p_1, feed, atm. x10^2	0.429	0.638	1.29	0.662	0.698
p_2, exit, atm. x10^2	0.310	0.465	0.658	0.223	0.290
P, av. tower, atm.	0.980	0.980	0.980	0.980	0.980
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0121	0.0173	0.00622	0.0465	0.0432
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.85	0.60	0.21	0.895	0.970
Over-all Coefficient:					
$K_L ah$, ft./hr.	20.5	34.0	34.8	53.3	42.6
$K_L a$, hr.$^{-1}$	17.8	29.6	30.3	46.3	37.1

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	212	213	214	215	216
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	5200	3700	2470	1870	1350
T_1, outlet, °F.	70.0	70.0	70.0	69.8	70.5
T_2, inlet, °F.	70.0	70.0	70.0	69.6	70.1
c_1, outlet, lb.-mol/ft.^{3}	0.000420	0.000456	0.000408	0.000359	0.000623
Moles SO_2 absorbed, $\frac{\text{lb.-mol}_2}{\text{hr. ft.}}$	0.0351	0.0271	0.0162	0.0108	0.0135
Gas Side Measurements:					
G, lb./hr.ft.^{2}	272	272	272	272	272
G_m, lb.-mol/hr.ft.^{2}	9.43	9.43	9.43	9.43	9.43
t_1, feed, °F.	70.0	70.0	69.8	69.8	71.0
t_2, exit, °F.	70.0	70.0	70.0	69.5	70.0
p_1, feed, atm. x10^2	0.659	0.569	0.447	0.285	0.961
p_2, exit, atm. x10^2	0.316	0.329	0.266	0.107	0.902
P, av. tower, atm.	0.980	0.980	0.980	0.980	0.980
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0335	0.0234	0.0176	0.0173	0.0157
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.955	0.863	1.09	1.60	1.16
Over-all Coefficient:					
$K_L a$, ft./hr.	35.5	32.4	23.2	28.6	9.00
$K_L a$, hr.$^{-1}$	30.9	28.2	20.2	24.9	7.82

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	242	243	244	245	246
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	11,000	7600	5400	3700	2640
T_1, outlet, °F.	70.0	70.0	69.9	69.9	70.0
T_2, inlet, °F.	69.0	69.2	70.0	70.1	70.5
c_1, outlet, lb.-mol/ft.^{3}	0.000531	0.000686	0.000854	0.00100	0.00104
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0940	0.0836	0.0740	0.0594	0.0441
Gas Side Measurements:					
G, lb./hr.ft.^{2}	424	424	424	424	424
G_m, lb.-mol/hr.ft.^{2}	16.5	16.5	16.5	16.5	16.5
t_1, feed, °F.	70.0	69.2	70.0	70.1	70.5
t_2, exit, °F.	70.0	70.0	69.9	69.9	70.0
p_1, feed, atm. x10^2	1.50	1.48	1.47	1.49	1.35
p_2, exit, atm. x10^2	0.533	0.495	0.799	0.864	0.848
P, av. tower, atm.	0.991	0.991	0.991	0.991	0.991
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}}$	0.177	0.174	0.118	0.122	0.121
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.87	2.08	1.60	2.05	2.74
Over-all Coefficient:					
$K_L a$, ft./hr.	58.1	57.7	39.9	36.1	29.1
$K_L a$, hr.$^{-1}$	50.5	50.2	34.7	31.4	25.3

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	247	248	249	250	251
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1850	1340	1050	11,000	5000
T_1, outlet, °F.	70.1	70.2	70.2	70.5	70.0
T_2, inlet, °F.	70.0	70.0	70.0	70.1	69.9
c_1, outlet, lb.-mol/ft.^{3}	0.00130	0.00145	0.00117	0.000114	0.000292
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0386	0.0312	0.0198	0.0202	0.0234
Gas Side Measurements:					
G, lb./hr.ft.^{2}	424	424	424	94.6	91.5
G_m, lb.-mol/hr.ft.^{2}	16.5	16.5	16.5	3.38	3.38
t_1, feed, °F.	70.0	70.5	70.5	71.0	67.0
t_2, exit, °F.	70.0	70.1	70.0	70.0	69.9
p_1, feed, atm. x10^2	1.51	1.59	1.07	0.627	0.873
p_2, exit, atm. x10^2	1.08	1.26	0.862	0.0682	0.150
P, av. tower, atm.	0.991	0.991	0.991	0.991	0.991
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0759	0.0585	0.0356	0.0198	0.0256
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.96	1.87	1.80	0.985	1.09
Over-all Coefficient:					
$K_L a$, ft./hr.	23.2	17.7	15.6	31.4	25.3
$K_L a$, hr.$^{-1}$	20.2	15.4	13.6	27.3	22.0

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	252	254	255	256	257
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	2290	1120	2290	5000	11,000
T_1, outlet, °F.	70.1	70.2	70.1	70.0	70.0
T_2, inlet, °F.	70.0	70.1	70.0	70.0	69.9
c_1, outlet, lb.-mol/ft.^{3}	0.000471	0.000191	0.000364	0.000473	0.000628
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0173	0.00343	0.0133	0.0378	0.0111
Gas Side Measurements:					
G, lb./hr.ft.^{2}	91.5	158	158	158	158
G_m, lb.-mol/hr.ft.^{2}	3.27	5.63	5.63	5.63	5.63
t_1, feed, °F.	70.0	67.0	68.9	69.9	70.2
t_2, exit, °F.	70.0	70.0	70.0	70.0	69.9
p_1, feed, atm. x10^2	0.754	0.736	0.718	1.03	1.89
p_2, exit, atm. x10^2	0.261	0.197	0.214	0.356	1.68
P, av. tower, atm.	0.991	0.978	0.978	0.978	0.978
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0175	0.0322	0.0288	0.0413	0.0132
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.01	0.950	0.985	1.09	1.17
Over-all Coefficient:					
$K_L a$, ft./hr.	19.4	3.54	18.8	31.8	42.2
$K_L a$, hr.$^{-1}$	16.9	3.08	16.4	27.7	36.7

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	258	259	260	261	262
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	11,000	5000	2290	1120	1120
T_1, outlet, °F.	70.0	70.0	70.0	70.0	70.0
T_2, inlet, °F.	70.0	70.0	70.0	70.0	69.5
c_1, outlet, lb.-mol/ft.^{3}	0.000290	0.000459	0.000657	0.000597	0.000856
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0513	0.0368	0.0242	0.0107	0.0154
Gas Side Measurements:					
G, lb./hr.ft.^{2}	226	226	226	226	338
G_m, lb.-mol/hr.ft.^{2}	8.07	8.07	8.07	8.07	12.0
t_1, feed, °F.	69.5	69.5	69.9	69.5	70.5
t_2, exit, °F.	70.0	70.0	70.0	69.5	70.0
p_1, feed, atm. x10^2	0.880	0.816	0.651	0.485	0.777
p_2, exit, atm. x10^2	0.275	0.395	0.518	0.374	0.679
P, av. tower, atm.	0.988	0.988	0.988	0.988	0.997
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0470	0.0356	0.0113	0.00891	0.00121
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.916	0.965	0.465	0.855	0.785
Over-all Coefficient:					
$K_L a$, ft./hr.	48.2	34.8	25.7	15.2	14.4
$K_L a$, hr.$^{-1}$	41.9	30.3	22.4	13.2	12.5

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	264	265	266	267	268
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	5000	11,000	11,000	5000	2290
T_1, outlet, °F.	70.0	70.1	71.0	71.0	70.1
T_2, inlet, °F.	70.0	70.0	70.5	70.0	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000467	0.000317	0.000373	0.000559	0.000795
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0375	0.0561	0.0660	0.0449	0.0292
Gas Side Measurements:					
G, lb./hr.ft.^{2}	338	338	420	500	522
G_m, lb.-mol/hr.ft.^{2}	12.0	12.0	15.0	17.9	18.6
t_1, feed, °F.	70.6	71.0	71.0	70.1	69.9
t_2, exit, °F.	70.0	70.0	71.0	70.0	70.0
p_1, feed, atm. x10^2	0.727	0.692	0.713	0.664	0.780
p_2, exit, atm. x10^2	0.425	0.261	0.266	0.403	0.592
P, av. tower, atm.	0.997	0.997	0.974	0.974	0.974
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.00376	0.00536	0.0715	0.00500	0.00443
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.00	0.955	1.08	1.11	1.51
Over-all Coefficient:					
$K_L a$, ft./hr.	37.0	59.6	69.5	49.8	28.3
$K_L a$, hr.$^{-1}$	32.2	51.8	60.5	43.3	24.6

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	269	270	271	272	273
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1120	1120	2290	5000	11,000
T_1, outlet, °F.	69.4	70.0	70.0	70.4	71.0
T_2, inlet, °F.	70.0	70.0	70.0	70.1	70.2
c_1, outlet, lb.-mol/ft.^{3}	0.000683	0.000596	0.000632	0.000628	0.000424
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0123	0.0107	0.0232	0.0504	0.0750
Gas Side Measurements:					
G, lb./hr.ft.^{2}	522	725	725	725	640
G_m, lb.-mol/hr.ft.^{2}	18.6	24.3	24.3	24.3	21.9
t_1, feed, °F.	70.0	70.5	70.5	71.1	73.0
t_2, exit, °F.	70.0	70.0	70.0	70.1	70.5
p_1, feed, atm. x10^2	0.472	0.411	0.526	0.597	0.512
p_2, exit, atm. x10^2	0.421	0.352	0.422	0.383	0.159
P, av. tower, atm.	0.974	0.980	0.980	0.980	0.980
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.000541	0.000616	0.000110	0.00226	0.00373
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.82	1.40	1.15	1.09	1.09
Over-all Coefficient:					
$K_L a$, ft./hr.	17.6	17.1	30.0	63.5	119
$K_L a$, hr.$^{-1}$	15.3	14.9	26.1	55.2	104

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	274	275	276	277	278
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1170	2350	3220	4400	5500
T_1, outlet, °F.	70.9	70.3	70.4	70.0	70.0
T_2, inlet, °F.	70.3	70.1	70.2	69.9	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000441	0.000609	0.000575	0.000508	0.000537
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.00829	0.0230	0.0297	0.0359	0.0386
Gas Side Measurements:					
G, lb./hr.ft.^{2}	278	278	278	278	278
G_m, lb.-mol/hr.ft.^{2}	9.68	9.61	9.61	9.61	9.61
t_1, feed, °F.	70.6	71.0	70.0	70.0	70.8
t_2, exit, °F.	70.5	70.1	70.2	71.0	70.0
p_1, feed, atm. x10^2	0.407	0.656	0.777	0.868	0.830
p_2, exit, atm. x10^2	0.280	0.474	0.491	0.515	0.456
P, av. tower, atm.	0.987	0.987	0.987	0.987	0.987
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0128	0.0185	0.0289	0.0358	0.0380
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.55	0.806	0.972	0.997	0.983
Over-all Coefficient:					
$K_L ah$, ft./hr.	12.6	24.7	28.3	37.0	34.1
$K_L a$, hr.$^{-1}$	11.0	21.5	24.6	32.2	30.0

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	279	280	281	282	283
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	2	2
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	7600	9400	11,100	800	1340
T_1, outlet, °F.	70.0	70.0	70.0	71.0	70.0
T_2, inlet, °F.	70.0	70.0	70.0	70.1	69.9
c_1, outlet, lb.-mol/ft.^{3}	0.000337	0.000274	0.000209	0.00124	0.00128
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0411	0.0411	0.0372	0.0158	0.0275
Gas Side Measurements:					
G, lb./hr.ft.^{2}	278	281	278	278	278
G_m, lb.-mol/hr.ft.^{2}	9.54	9.79	9.69	9.58	9.58
t_1, feed, °F.	71.0	71.0	71.2	72.6	71.4
t_2, exit, °F.	70.0	70.0	70.0	70.2	69.9
p_1, feed, atm. x10^2	0.678	0.630	0.613	0.795	0.909
p_2, exit, atm. x10^2	0.303	0.243	0.201	0.629	0.681
P, av. tower, atm.	0.987	0.987	0.987	0.981	0.981
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0375	0.0397	0.0418	0.0188	0.0232
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.912	0.964	1.12	1.19	0.843
Over-all Coefficient:					
$K_L a$, ft./hr.	44.1	46.6	43.2	11.4	30.9
$K_L a$, hr.$^{-1}$	38.4	40.5	37.6	5.33	14.4

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	284	285	286	287	288
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	2
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1930	2670	3720	5280	7800
T_1, outlet, °F.	70.0	70.1	70.5	70.0	70.4
T_2, inlet, °F.	69.9	70.0	70.1	69.9	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.00123	0.00142	0.00136	0.00120	0.000884
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0381	0.0609	0.0812	0.102	0.110
Gas Side Measurements:					
G, lb./hr.ft.^{2}	277	277	277	277	277
G_m, lb.-mol/hr.ft.^{2}	9.56	9.56	9.56	9.56	9.56
t_1, feed, °F.	70.0	70.3	71.1	70.4	71.1
t_2, exit, °F.	70.8	70.0	70.1	70.0	70.0
p_1, feed, atm. x10^2	0.994	1.45	1.58	1.75	1.45
p_2, exit, atm. x10^2	0.661	0.876	0.800	0.554	0.234
P, av. tower, atm.	0.981	0.981	0.981	0.981	0.981
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0352	0.0606	0.0816	0.0125	0.124
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.925	0.995	1.01	1.22	1.17
Over-all Coefficient:					
$K_L a$, ft./hr.	36.6	43.1	55.2	68.9	106
$K_L a$, hr.$^{-1}$	17.1	20.1	25.8	32.2	49.5

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	289	310	311	312	313
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	2
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	11,100	720	1360	1910	2610
T_1, outlet, °F.	70.5	71.0	70.0	70.0	70.0
T_2, inlet, °F.	70.1	70.1	69.6	70.0	69.9
c_1, outlet, lb.-mol/ft.^{3}	0.000715	0.00104	0.000743	0.000651	0.000646
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.127	0.0121	0.0162	0.0200	0.0271
Gas Side Measurements:					
G, lb./hr.ft.^{2}	270	275	278	278	278
G_m, lb.-mol/hr.ft.^{2}	9.39	9.50	9.66	9.70	9.70
t_1, feed, °F.	73.1	71.3	70.8	70.2	70.0
t_2, exit, °F.	70.1	70.5	70.0	70.0	70.0
p_1, feed, atm. x10^2	1.41	0.780	0.473	0.474	0.528
p_2, exit, atm. x10^2	0.116	0.682	0.342	0.290	0.278
P, av. tower, atm.	0.981	0.987	0.987	0.987	0.987
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0138	0.00987	0.0132	0.0182	0.0255
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.02	0.820	0.820	0.910	0.940
Over-all Coefficient:					
$K_L ah$, ft./hr.	128	14.2	27.3	32.2	40.8
$K_L a$, hr.$^{-1}$	59.8	12.4	12.7	15.0	19.1

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	314	315	316	317	318
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	2	2	2	2	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	3820	5300	7750	11,200	1120
T_1, outlet, °F.	70.0	70.0	70.4	70.9	70.4
T_2, inlet, °F.	70.0	70.0	70.1	70.4	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000537	0.000465	0.000382	0.000317	0.000569
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0330	0.0396	0.0474	0.0571	0.0102
Gas Side Measurements:					
G, lb./hr.ft.^{2}	278	278	272	272	68
G_m, lb.-mol/hr.ft.^{2}	9.70	9.70	9.41	9.41	2.40
t_1, feed, °F.	69.9	69.5	69.5	71.5	70.1
t_2, exit, °F.	70.0	70.0	70.1	70.4	70.0
p_1, feed, atm. x10^2	0.568	0.611	0.673	0.634	0.596
p_2, exit, atm. x10^2	0.250	0.206	0.145	0.0788	0.380
P, av. tower, atm.	0.987	0.987	0.987	0.987	0.988
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0321	0.0412	0.0519	0.0544	0.00564
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.972	1.04	1.09	0.953	0.551
Over-all Coefficient:					
$K_L a$, ft./hr.	41.2	53.4	66.8	100	12.0
$K_L a$, hr.$^{-1}$	19.2	25.0	31.2	46.7	10.4

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	319	320	321	322	323
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1540	2270	3320	4940	7050
T_1, outlet, °F.	70.4	70.3	70.5	70.0	70.1
T_2, inlet, °F.	70.0	70.0	70.1	69.8	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000365	0.000268	0.000186	0.000315	0.000226
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.00902	0.00978	0.00993	0.0250	0.0255
Gas Side Measurements:					
G, lb./hr.ft.^{2}	68	68	68	68	68
G_m, lb.-mol/hr.ft.^{2}	2.40	2.40	2.40	2.40	2.40
t_1, feed, °F.	70.0	70.0	69.8	69.4	69.2
t_2, exit, °F.	70.0	70.0	70.1	69.9	70.0
p_1, feed, atm. x10^2	0.562	0.587	0.530	1.10	0.607
p_2, exit, atm. x10^2	0.200	0.257	0.147	0.119	0.116
P, av. tower, atm.	0.988	0.988	0.988	0.988	0.988
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.00912	0.00825	0.0961	0.0240	0.0124
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.01	1.06	0.970	0.960	0.485
Over-all Coefficient:					
$K_L ah$, ft./hr.	12.0	11.1	13.7	25.0	25.9
$K_L a$, hr.$^{-1}$	10.4	9.65	11.9	21.8	22.5

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	327	328	329	330	333
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1130	1500	2280	3300	1490
T_1, outlet, °F.	70.0	70.0	70.0	70.0	70.5
T_2, inlet, °F.	70.0	70.0	70.0	70.0	70.5
c_1, outlet, lb.-mol/ft.^{3}	0.000491	0.000377	0.000328	0.000302	0.000440
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.00889	0.00908	0.0120	0.0160	0.0105
Gas Side Measurements:					
G, lb./hr.ft.^{2}	173	173	173	173	240
G_m, lb.-mol/hr.ft.^{2}	6.05	6.05	6.05	6.05	8.39
t_1, feed, °F.	69.2	70.0	70.7	70.8	72.2
t_2, exit, °F.	70.2	70.0	70.0	70.0	70.5
p_1, feed, atm. x10^2	0.451	0.370	0.393	0.441	0.380
p_2, exit, atm. x10^2	0.310	0.218	0.200	0.167	0.262
P, av. tower, atm.	0.980	0.980	0.980	0.980	0.982
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.00810	0.00968	0.0126	0.0212	0.0128
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.912	1.07	1.05	1.32	1.22
Over-all Coefficient:					
$K_L a$, ft./hr.	12.6	15.3	19.0	25.4	16.9
$K_L a$, hr.$^{-1}$	10.9	13.3	16.5	22.1	14.7

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	334	337	339	342	343
Temperature, °F.	70	70	70	70	70
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	3310	1130	1510	1500	3300
T_1, outlet, °F.	70.6	70.6	70.0	71.6	70.1
T_2, inlet, °F.	70.4	70.1	69.9	71.0	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000370	0.000584	0.000440	0.000820	0.000595
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0197	0.0106	0.0106	0.0198	0.0315
Gas Side Measurements:					
G, lb./hr.ft.^{2}	240	342	342	492	492
G_m, lb.-mol/hr.ft.^{2}	8.39	12.1	12.0	17.0	17.0
t_1, feed, °F.	71.5	73.0	74.0	73.0	70.9
t_2, exit, °F.	70.4	70.1	70.0	71.0	70.0
p_1, feed, atm. x10^2	0.542	0.459	0.387	0.713	0.700
p_2, exit, atm. x10^2	0.300	0.369	0.300	0.594	0.511
P, av. tower, atm.	0.983	0.988	0.988	0.982	0.971
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0170	0.0100	0.0104	0.0296	0.0343
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.864	0.943	0.981	1.16	1.09
Over-all Coefficient:					
$K_L a$h, ft./hr.	27.2	14.7	16.1	19.9	30.6
$K_L a$, hr.$^{-1}$	23.6	12.8	14.0	17.3	26.6

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	345	346	391	392	393
Temperature, °F.	70	70	50	50	50
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1510	3300	1130	2000	3500
T_1, outlet, °F.	70.4	70.6	51.1	51.0	51.0
T_2, inlet, °F.	70.0	70.0	50.1	50.1	50.0
c_1, outlet, lb.-mol/ft.^{3}	0.000859	0.000531	0.00158	0.00104	0.000887
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0208	0.0281	0.0286	0.0334	0.0498
Gas Side Measurements:					
G, lb./hr.ft.^{2}	731	724	603	605	605
G_m, lb.-mol/hr.ft.^{2}	25.2	25.0	20.8	20.9	20.9
t_1, feed, °F.	72.0	71.8	54.0	53.4	53.0
t_2, exit, °F.	70.0	70.0	51.0	50.5	50.5
p_1, feed, atm. x10^2	0.694	0.448	1.14	0.834	0.916
p_2, exit, atm. x10^2	0.608	0.335	1.07	0.718	0.699
P, av. tower, atm.	0.979	0.978	0.996	0.996	0.996
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0202	0.0345	0.0212	0.0253	0.0480
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.971	1.23	0.741	0.757	0.964
Over-all Coefficient:					
$K_L a h$, ft./hr.	21.4	40.1	9.72	14.50	25.20
$K_L a$, hr.$^{-1}$	18.6	34.9	8.45	12.6	22.0

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	394	395	396	397	398
Temperature, °F.	50	50	50	50	50
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	6200	11,000	11,000	6200	3500
T_1, outlet, °F.	50.1	50.2	49.9	50.0	50.2
T_2, inlet, °F.	50.0	50.1	49.8	49.9	50.0
c_1, outlet, lb.-mol/ft.^{3}	0.000717	0.000540	0.000300	0.000476	0.000652
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0717	0.0956	0.0531	0.0476	0.0366
Gas Side Measurements:					
G, lb./hr.ft.^{2}	608	530	292	292	292
G_m, lb.-mol/hr.ft.^{2}	21.0	18.5	10.2	10.2	10.2
t_1, feed, °F.	53.0	53.1	53.8	54.3	54.3
t_2, exit, °F.	50.0	50.1	50.0	50.1	50.2
p_1, feed, atm. x10^2	0.886	0.909	0.818	0.842	0.837
p_2, exit, atm. x10^2	0.569	0.352	0.263	0.422	0.496
P, av. tower, atm.	0.996	0.996	1.00	1.00	1.00
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0708	0.109	0.0601	0.0457	0.0372
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.987	1.14	1.13	0.960	1.02
Over-all Coefficient:					
$K_L a$, ft./hr.	38.0	42.9	32.5	26.7	20.6
$K_L a$, hr.$^{-1}$	33.0	37.4	28.3	23.2	17.9

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	399	400	401	402	403
Temperature, °F.	90	90	90	90	90
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1130	2000	3500	6200	11,000
T_1, outlet, °F.	90.1	90.0	91.1	90.0	90.0
T_2, inlet, °F.	90.6	90.2	90.0	90.0	90.0
c_1, outlet, lb.-mol/ft.^{3}	0.000633	0.0006085	0.000736	0.000553	0.000427
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0114	0.0195	0.0414	0.0553	0.0756
Gas Side Measurements:					
G, lb./hr.ft.^{2}	546	546	546	546	495
G_m, lb.-mol/hr.ft.^{2}	18.6	18.6	18.6	18.6	18.6
t_1, feed, °F.	91.1	90.1	91.1	91.0	90.1
t_2, exit, °F.	90.1	90.2	90.0	90.0	90.0
p_1, feed, atm. x10^2	0.594	0.668	1.16	1.01	1.05
p_2, exit, atm. x10^2	0.557	0.597	0.944	0.737	0.481
P, av. tower, atm.	0.994	0.994	0.994	0.994	0.994
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0725	0.0140	0.0448	0.0550	0.0113
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.636	0.718	1.08	0.995	1.49
Over-all Coefficient:					
$K_L a h$, ft./hr.	20.8	32.7	42.5	60.4	89
$K_L a$, hr.$^{-1}$	18.1	27.6	37.0	52.5	77.5

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	404	405	406	407	408
Temperature, °F.	90	90	90	90	90
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	11,000	6200	3500	6200	11,000
T_1, outlet, °F.	89.8	89.6	90.0	90.0	90.0
T_2, inlet, °F.	89.9	89.6	90.0	90.0	90.0
c_1, outlet, lb.-mol/ft.^{3}	0.000294	0.000437	0.000706	0.000400	0.000331
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0520	0.0437	0.0397	0.0400	0.0586
Gas Side Measurements:					
G, lb./hr.ft.^{2}	273	273	274	274	268
G_m, lb.-mol/hr.ft.^{2}	9.35	9.45	9.25	9.30	9.10
t_1, feed, °F.	89.1	92.1	90.0	90.0	92.0
t_2, exit, °F.	89.9	89.9	90.0	90.0	90.0
p_1, feed, atm. x10^2	1.06	1.10	1.08	0.979	1.19
p_2, exit, atm. x10^2	0.401	0.670	0.999	0.606	0.501
P, av. tower, atm.	0.994	0.994	0.989	0.989	0.989
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0667	0.0426	0.0908	0.0375	0.0675
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.28	0.975	0.228	0.938	1.15
Over-all Coefficient:					
$K_L ah$, ft./hr.	59.2	44.5	39.2	43.8	59.5
$K_L a$, hr.$^{-1}$	51.5	38.8	34.2	38.3	51.8

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	409	410	411	412	413
Temperature, °F.	90	90	90	90	90
Packed Height, ft.	1	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1130	2000	3500	6200	11,000
T_1, outlet, °F.	90.0	90.1	90.0	90.0	90.0
T_2, inlet, °F.	90.0	90.1	90.0	90.0	90.0
c_1, outlet, lb.-mol/ft.^{3}	0.000997	0.000531	0.000443	0.000270	0.000184
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0180	0.0171	0.0249	0.0270	0.0325
Gas Side Measurements:					
G, lb./hr.ft.^{2}	94.5	94.5	94.5	94.5	94.5
G_m, lb.-mol/hr.ft.^{2}	3.17	3.06	3.06	3.06	3.06
t_1, feed, °F.	91.0	90.8	90.1	90.6	91.0
t_2, exit, °F.	90.0	90.1	90.0	90.0	90.0
p_1, feed, atm. x10^2	1.62	1.08	1.21	1.19	1.37
p_2, exit, atm. x10^2	1.17	0.606	0.543	0.359	0.249
P, av. tower, atm.	0.989	0.989	0.989	0.989	0.989
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.158	0.0156	0.0223	0.0274	0.0372
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.877	0.911	0.895	1.01	1.14
Over-all Coefficient:					
$K_L ah$, ft./hr.	14.4	19.3	25.8	30.6	37.7
$K_L a$, hr.$^{-1}$	12.5	16.8	22.4	26.6	32.8

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	414	415	416	417
Temperature, °F.	70	70	70	70
Packed Height, ft.	1	1	1	1
System	H_2O	H_2O	H_2O	H_2O
Liquor Side Measurements:				
L, lb./hr.ft.^{2}	1130	1500	2280	3300
T_1, outlet, °F.	--	--	--	--
T_2, inlet, °F.	70.2	70.2	70.0	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.00139	0.00135	0.00118	0.000987
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0254	0.0328	0.0435	0.0523
Gas Side Measurements:				
G, lb./hr.ft.^{2}	710	730	730	724
G_m, lb.-mol/hr.ft.^{2}	24.5	25.0	25.0	24.8
t_1, feed, °F.	73.0	71.0	71.0	70.5
t_2, exit, °F.	71.0	70.2	70.1	70.0
p_1, feed, atm. x10^2	1.30	1.26	1.14	1.05
p_2, exit, atm. x10^2	1.09	1.17	0.905	0.790
P, av. tower, atm.	0.983	0.983	0.983	0.983
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0245	0.0275	0.0625	0.0690
Material Balance:				
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.965	0.840	1.43	1.32
Over-all Coefficient:				
$K_L a h$, ft./hr.	19.4	23.8	32.4	41.1
$K_L a$, hr.$^{-1}$	16.9	20.7	28.2	35.8

TABLE XIX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO WATER. SUMMARY OF DATA.

Run No.	418	419	420
Temperature, °F.	70	70	70
Packed Height, ft.	1	1	1
System	H_2O	H_2O	H_2O
Liquor Side Measurements:			
L, lb./hr.ft.^{2}	4990	7000	11,000
T_1, outlet, °F.	--	--	--
T_2, inlet, °F.	70.0	70.0	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000766	0.000628	0.000459
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0617	0.0709	0.0820
Gas Side Measurements:			
G, lb./hr.ft.^{2}	731	708	675
G_m, lb.-mol/hr.ft.^{2}	25.4	24.7	23.6
t_1, feed, °F.	71.0	72.0	73.0
t_2, exit, °F.	70.0	70.3	70.5
p_1, feed, atm. x10^2	0.873	0.703	0.564
p_2, exit, atm. x10^2	0.615	0.392	0.189
P, av. tower, atm.	0.983	0.983	0.983
Moles SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0691	0.0818	0.0935
Material Balance:			
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.12	1.15	1.14
Over-all Coefficient:			
$K_L a h$, ft./hr.	53.6	74.5	113
$K_L a$, hr.$^{-1}$	47.7	64.8	98.4

TABLE XX

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO 0.058 MOLAL SULFURIC ACID. SUMMARY OF DATA.

Run No.	349	350	351	352	353
Temperature, °F.	70	70	70	70	70
Packed height, ft.	1	1	1	1	1
System	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1130	1490	2280	3300	4950
T_1, outlet, °F.	70.6	70.0	70.0	70.0	70.0
T_2, inlet, °F.	70.9	70.0	69.9	69.9	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000520	0.000488	0.000412	0.000345	0.000244
Moles SO_2 absorbed, $\frac{\text{lb.-mol}_2}{\text{hr. ft.}}$	0.00941	0.0117	0.0151	0.0183	0.0194
Gas Side Measurements:					
G, lb./hr.ft.^{2}	500	500	500	500	532
G_m, lb.-mol/hr.ft.^{2}	17.3	17.3	17.3	17.3	18.2
t_1, feed, °F.	69.9	69.8	69.1	70.6	71.0
t_2, exit, °F.	70.9	70.0	70.0	69.9	70.0
p_1, feed, atm. x10^2	0.905	0.821	0.857	0.802	1.44
p_2, exit, atm. x10^2	0.981	0.981	0.981	0.981	0.981
P, av. tower, atm.	0.859	0.780	0.762	0.707	1.22
Moles, SO_2 lost, $\frac{\text{lb.-mol}_2}{\text{hr. ft.}^2}$	0.00847	0.0076	0.0176	0.0171	0.0455
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.900	0.650	1.16	0.934	2.34
Over-all Coefficient:					
$K_L ah$, ft./hr.	13.4	18.4	23.0	29.5	17.0
$K_L a$, hr.$^{-1}$	11.6	16.0	20.0	25.7	14.8

TABLE XX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO 0.058 MOLAL SULFURIC ACID. SUMMARY OF DATA.

Run No.	354	355	356	357	358
Temperature, °F.	70	70	70	70	70
Packed height, ft.	1	1	1	1	1
System	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	6990	11,000	1130	1500	2340
T_1, outlet, °F.	70.0	70.2	70.4	70.0	70.0
T_2, inlet, °F.	70.0	70.0	70.6	70.0	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000200	0.000121	0.000881	0.000778	0.000551
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0224	0.0214	0.0159	0.0187	0.0207
Gas Side Measurements:					
G, lb./hr.ft.^{2}	532	500	731	731	731
G_m, lb.-mol/hr.ft.^{2}	18.4	17.4	25.0	25.0	25.0
t_1, feed, °F.	71.0	72.0	70.8	70.2	70.5
t_2, exit, °F.	70.0	70.0	70.6	70.0	70.0
p_1, feed, atm. x10^2	0.720	0.552	1.37	1.24	0.990
p_2, exit, atm. x10^2	0.534	0.357	1.30	1.19	0.916
P, av. tower, atm.	0.981	0.983	0.974	0.974	0.974
Moles, SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0364	0.0358	0.0210	0.0130	0.0208
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.63	1.67	1.31	0.70	1.00
Over-all Coefficient:					
$K_L a$, ft./hr.	42.2	55.0	15.9	19.1	25.9
$K_L a$, hr.$^{-1}$	36.7	47.8	13.8	16.6	22.5

TABLE XX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO 0.058 MOLAL SULFURIC ACID. SUMMARY OF DATA.

Run No.	359	361	362	363	364
Temperature, °F.	70	70	70	70	70
Packed height, ft.	1	1	1	1	1
System	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	3300	7000	11,000	1130	1500
T_1, outlet, °F.	70.2	70.5	70.2	71.0	70.1
T_2, inlet, °F.	70.1	70.0	70.1	70.8	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000463	0.000283	0.000185	0.000756	0.000805
Moles SO_2 absorbed, $\frac{\text{lb.-mol}_2}{\text{hr. ft.}}$	0.0245	0.0317	0.0327	0.0137	0.0194
Gas Side Measurements:					
G, lb./hr.ft.^{2}	731	680	600	161	164
G_m, lb.-mol/hr.ft.^{2}	25.0	23.3	20.7	5.51	5.60
t_1, feed, °F.	70.8	72.3	73.1	71.0	69.0
t_2, exit, °F.	70.1	70.0	70.1	70.8	70.0
p_1, feed, atm. x10^2	0.869	0.887	1.19	1.44	1.64
p_2, exit, atm. x10^2	0.781	0.952	0.774	1.25	1.40
P, av. tower, atm.	0.974	0.973	0.973	0.964	0.964
Moles, SO_2 lost, $\frac{\text{lb.-mol}_2}{\text{hr. ft.}}$	0.0232	0.0172	0.0112	0.0114	0.0147
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.947	0.540	0.342	0.832	0.758
Over-all Coefficient:					
$K_L ah$, ft./hr.	35.0	35.4	32.4	12.0	14.8
$K_L a$, hr.$^{-1}$	30.4	30.8	28.2	10.4	12.9

TABLE XX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO 0.058 MOLAL SULFURIC ACID. SUMMARY OF DATA.

Run No.	365	366	367	368	369
Temperature, °F.	70	70	70	70	70
Packed height, ft.	1	1	1	1	1
System	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	2280	3300	4940	7000	11,000
T_1, outlet, °F.	70.0	70.0	70.1	70.0	70.1
T_2, inlet, °F.	70.0	69.9	70.0	70.0	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000754	0.000592	0.000428	0.000332	0.000242
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0276	0.0314	0.0339	0.0372	0.0428
Gas Side Measurements:					
G, lb./hr.ft.^{2}	164	164	164	161	149
G_m, lb.-mol/hr.ft.^{2}	5.60	5.60	5.60	5.51	5.14
t_1, feed, °F.	70.0	70.1	70.3	70.6	70.8
t_2, exit, °F.	70.0	70.0	70.0	70.0	70.0
p_1, feed, atm. x10^2	1.78	1.68	1.78	1.60	1.67
p_2, exit, atm. x10^2	1.40	1.23	1.07	0.960	0.745
P, av. tower, atm.	0.962	0.962	0.962	0.962	0.961
Moles, SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0234	0.0271	0.0442	0.0386	0.0525
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.848	0.863	1.30	1.03	1.23
Over-all Coefficient:					
$K_L a$, ft./hr.	19.4	23.4	24.4	29.0	34.6
$K_L a$, hr.$^{-1}$	16.9	20.4	21.2	25.2	30.1

TABLE XX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO 0.058 MOLAL SULFURIC ACID. SUMMARY OF DATA.

Run No.	370	371	372	373	374
Temperature, °F.	70	70	70	70	70
Packed height, ft.	1	1	1	1	1
System	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1130	1500	2330	3300	4950
T_1, outlet, °F.	70.6	70.1	69.9	69.8	70.0
T_2, inlet, °F.	70.8	70.2	70.0	70.0	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000644	0.000612	0.000500	0.000417	0.000356
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0116	0.0147	0.0187	0.0221	0.0283
Gas Side Measurements:					
G, lb./hr.ft.^{2}	234	234	234	234	234
G_m, lb.-mol/hr.ft.^{2}	7.99	7.99	7.99	7.99	7.99
t_1, feed, °F.	69.3	69.2	69.0	69.0	69.0
t_2, exit, °F.	70.8	70.2	70.0	70.0	70.0
p_1, feed, atm. x10^2	1.15	1.15	1.05	1.03	1.14
p_2, exit, atm. x10^2	1.06	1.03	0.841	0.722	0.738
P, av. tower, atm.	0.972	0.972	0.972	0.972	0.972
Moles, SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.00831	0.0107	0.0176	0.0266	0.0342
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.716	0.730	0.941	1.20	1.20
Over-all Coefficient:					
$K_L ah$, ft./hr.	12.5	15.9	22.9	28.3	32.2
$K_L a$, hr.$^{-1}$	10.9	13.8	19.9	24.6	28.0

TABLE XX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO 0.058 MOLAL SULFURIC ACID. SUMMARY OF DATA.

Run No.	375	376	377	378	379
Temperature, °F.	70	70	70	70	70
Packed height, ft.	1	1	1	1	1
System	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	7000	11,000	1130	1500	2330
T_1, outlet, °F.	70.1	69.9	70.0	70.0	70.0
T_2, inlet, °F.	70.0	70.0	70.0	70.0	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000313	0.000228	0.000722	0.000499	0.000439
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0350	0.0404	0.0131	0.0120	0.0164
Gas Side Measurements:					
G, lb./hr.ft.^{2}	234	234	345	345	345
G_m, lb.-mol/hr.ft.^{2}	7.99	7.99	11.8	11.8	11.8
t_1, feed, °F.	69.0	69.0	70.8	71.5	71.2
t_2, exit, °F.	70.0	70.0	70.0	70.0	70.0
p_1, feed, atm. x10^2	1.21	1.23	1.30	1.04	0.982
p_2, exit, atm. x10^2	0.734	0.664	1.24	0.980	0.858
P, av. tower, atm.	0.972	0.972	0.984	0.984	0.984
Moles, SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0405	0.0489	0.00802	0.00825	0.0156
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.16	1.21	0.612	0.687	0.951
Over-all Coefficient:					
$K_L a$, ft./hr.	37.2	42.1	12.3	13.4	20.0
$K_L a$, hr.$^{-1}$	32.4	36.6	10.7	11.6	17.4

TABLE XX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO 0.058 MOLAL SULFURIC ACID. SUMMARY OF DATA.

Run No.	380	381	382	383	384
Temperature, °F.	70	70	70	70	70
Packed height, ft.	1	1	1	1	1
System	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	3300	4950	7000	11,000	1130
T_1, outlet, °F.	70.1	70.1	70.1	70.0	70.6
T_2, inlet, °F.	70.0	70.0	70.0	70.1	70.8
c_1, outlet, lb.-mol/ft.^{3}	0.000424	0.000349	0.000307	0.000235	0.000754
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0225	0.0277	0.0344	0.0416	0.0136
Gas Side Measurements:					
G, lb./hr.ft.^{2}	330	330	330	330	99
G_m, lb.-mol/hr.ft.^{2}	11.8	11.8	11.8	11.8	3.48
t_1, feed, °F.	71.0	70.8	70.6	71.0	69.0
t_2, exit, °F.	70.0	70.0	70.0	70.1	70.5
p_1, feed, atm. x10^2	1.08	1.14	1.16	1.12	1.63
p_2, exit, atm. x10^2	0.960	.107	0.870	0.707	1.49
P, av. tower, atm.	0.984	0.984	0.984	0.984	1.00
Moles, SO_2 lost, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0156	0.0216	0.0374	0.0522	0.00536
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.693	0.780	1.09	1.25	0.39
Over-all Coefficient:					
$K_L a h$, ft./hr.	23.9	25.9	34.6	45.6	9.85
$K_L a$, hr.$^{-1}$	20.8	22.5	30.1	39.7	8.56

TABLE XX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO 0.058 MOLAL SULFURIC ACID. SUMMARY OF DATA.

Run No.	385	386	387	388	389
Temperature, °F.	70	70	70	70	70
Packed height, ft.	1	1	1	1	1
System	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
Liquor Side Measurements:					
L, lb./hr.ft.^{2}	1500	2280	3320	4950	7000
T_1, outlet, °F.	70.1	70.0	70.0	70.0	70.0
T_2, inlet, °F.	70.1	70.1	70.0	70.0	70.0
c_1, outlet, lb.-mol/ft.^{3}	0.000680	0.000527	0.000356	0.000309	0.000232
Moles SO_2 absorbed, $\frac{\text{lb.-mol}_2}{\text{hr. ft.}^2}$	0.0164	0.0197	0.0189	0.0246	0.0260
Gas Side Measurements:					
G, lb./hr.ft.^{2}	99	99	99	99	99
G_m, lb.-mol/hr.ft.^{2}	3.48	3.48	3.48	3.48	3.48
t_1, feed, °F.	71.1	69.0	70.0	71.5	72.0
t_2, exit, °F.	70.0	70.1	70.0	70.0	70.0
p_1, feed, atm. x10^2	1.52	1.50	1.28	1.45	1.38
p_2, exit, atm. x10^2	1.20	1.04	0.815	0.742	0.581
P, av. tower, atm.	1.00	1.00	1.00	1.00	1.00
Moles SO_2 lost, $\frac{\text{lb.-mol}_2}{\text{hr. ft.}^2}$	0.0121	0.0169	0.0183	0.0256	0.0293
Material Balance:					
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	0.740	0.858	0.968	1.04	1.13
Over-all Coefficient:					
$K_L a$, ft./hr.	13.8	16.7	19.1	22.8	26.3
$K_L a$, hr.$^{-1}$	12.0	14.5	16.6	19.8	22.9

TABLE XX (Continued)

THE ABSORPTION OF SULFUR DIOXIDE FROM GASES OF LOW CONCENTRATION INTO 0.058 MOLAL SULFURIC ACID. SUMMARY OF DATA.

Run No.	390
Temperature, °F.	70
Packed height, ft.	1
System	H_2SO_4
Liquor Side Measurements:	
L, lb./hr.ft.^{2}	11,000
T_1, outlet, °F.	70.1
T_2, inlet, °F.	70.1
c_1, outlet, lb.-mol/ft.^{3}	0.000156
Moles SO_2 absorbed, $\frac{\text{lb.-mol}}{\text{hr. ft.}^2}$	0.0276
Gas Side Measurements:	
G, lb./hr.ft.^{2}	99
G_m, lb.-mol/hr.ft.^{2}	3.25
t_1, feed, °F.	72.2
t_2, exit, °F.	70.1
p_1, feed, atm. x10^2	1.39
p_2, exit, atm. x10^2	0.491
P, av. tower, atm.	1.00
Moles SO_2 lost, $\frac{\text{lb.-mol}_2}{\text{hr. ft.}}$	0.0330
Material Balance:	
$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}}$	1.19
Over-all Coefficient:	
$K_L a h$, ft./hr.	30.4
$K_L a$, hr.$^{-1}$	26.4

APPENDIX II

DESCRIPTION OF ABSORPTION TOWER AND TOWER AUXILIARIES

The general design of the absorption tower is taken from that used by Whitney and Vivian (7). Considerations dictating the design of the system are as follows:

1. Provision for a closed cycle on the gas side to avoid the necessity of wasting the tower exit gases.

2. Provision for a closed system tight enough to permit the use of nitrogen as the inert gas to the exclusion of air.

3. Provision for the continuous analysis of the tower feed and exit gases.

A. THE LIQUOR SUPPLY SYSTEM

The liquor supply system comprises a 400-gallon rubber-lined steel tank equipped with a Mission 10-gallon per minute stainless steel recirculation pump and a 1-cubic foot capacity head tank. A pump throttle and differential manometer permit control of the head tank liquor feed rate. A concentric heat exchanger runs for five feet of the pump discharge line and serves for either heating or cooling the liquor. The head tank discharges through a stainless steel delivery line to the tower. A tubular heat exchanger on the pipe serves to heat

the feed liquor to the desired temperature by means of steam. Flow of steam to the heat exchanger on the liquor delivery line can be controlled by means of a solenoid valve actuated by a vacuum tube relay operated by a Merc-to-Merc temperature regulator. A 0.46-inch square-edged orifice, whose taps go to mercury and carbon tetrachloride manometers, permits flow measurement. Flow rate is adjusted by means of Hoffman compressor clamps on the rubber hose going to the tower.

B. THE ABSORPTION TOWER

The tower is constructed of Lucite methyl methacrylate polymer which is adequately stable over the temperature range of interest and is resistant to the chemicals used. The assembled tower may be considered to consist of three parts: (1) The liquor distribution and downcomer section (Figures 31 and 32), (2) the packed section, and (3) the gas upcomer section (Figures 33 and 34).

The liquor downcomer section actually consists of two subsections—the liquor distribution section and the gas expansion section. The liquor distributor section receives the flow of liquor through four stainless steel liquor entry tubes, the lower ends of which are below the edge of a liquor distribution weir. The liquor flows over the edge of the weir and into twelve 9-mm. glass tubes which function as downcomers to distribute the flow of liquor over the top of the packing. A 3 1/2-inch central tube, concentric with the tower, carries the exit gases out of the tower.

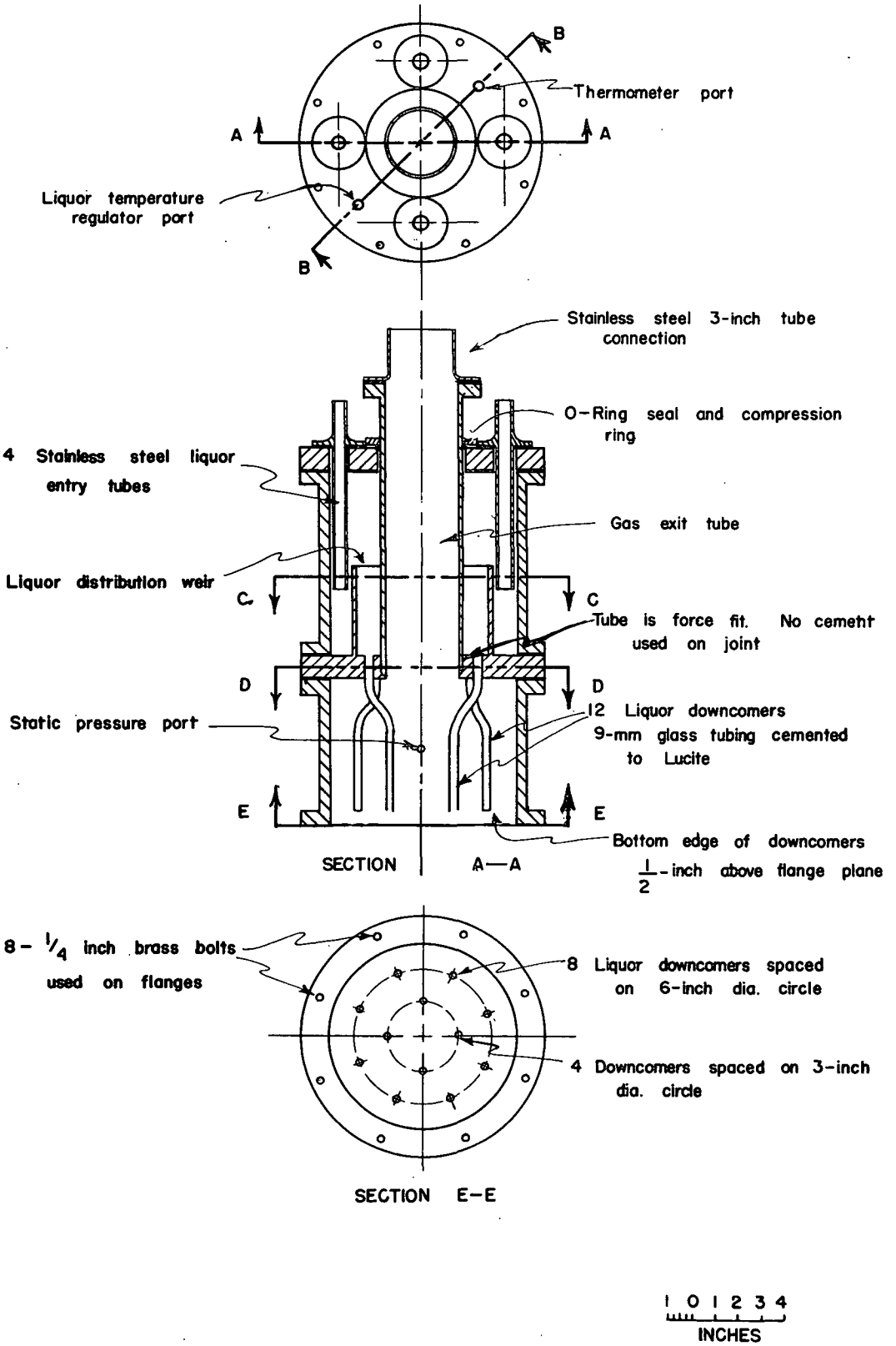


FIGURE 31. Absorption Tower Details: Liquor Downcomer Section

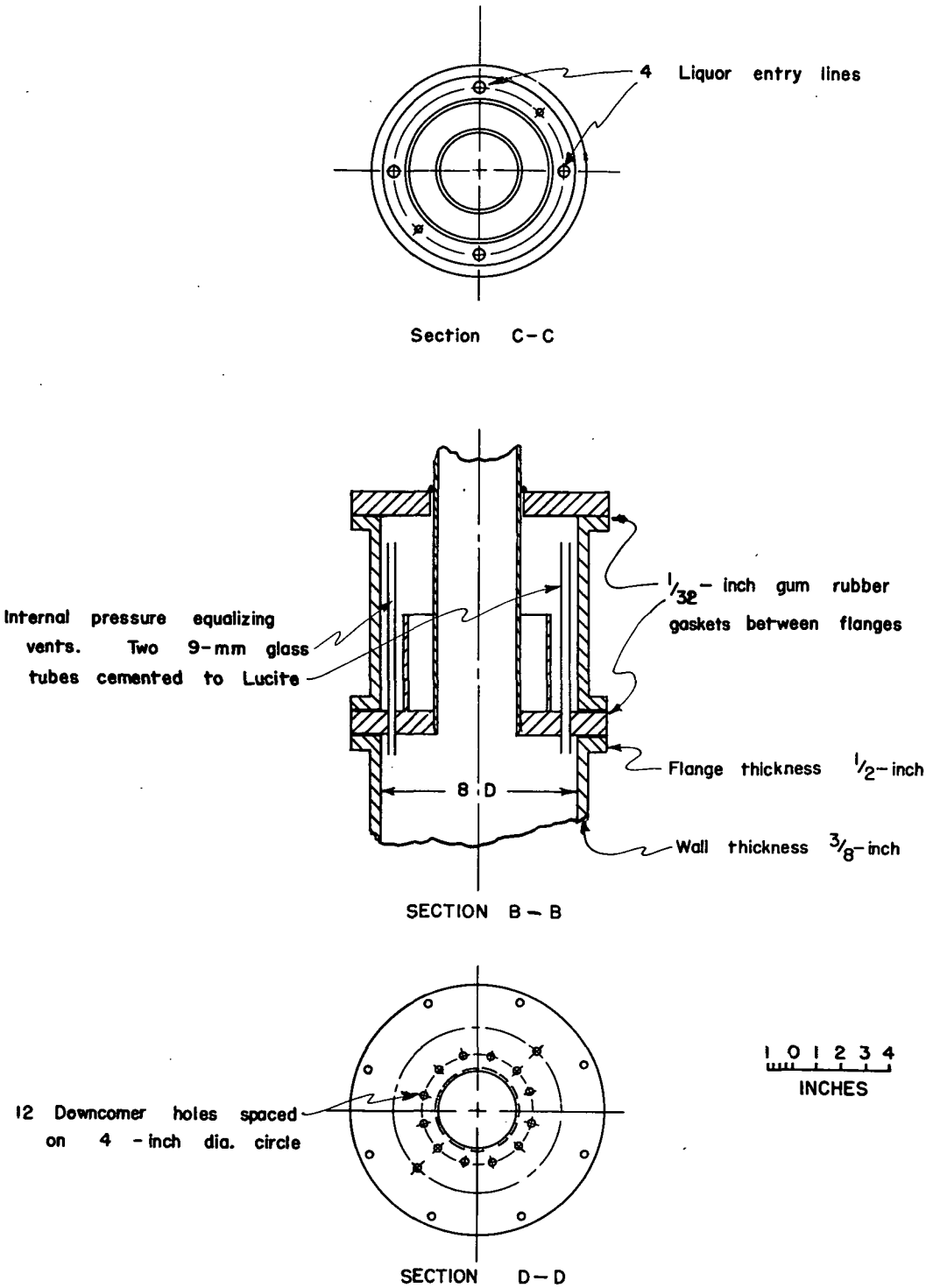


FIGURE 32. Absorption Tower Details: Liquor Downcomer Section

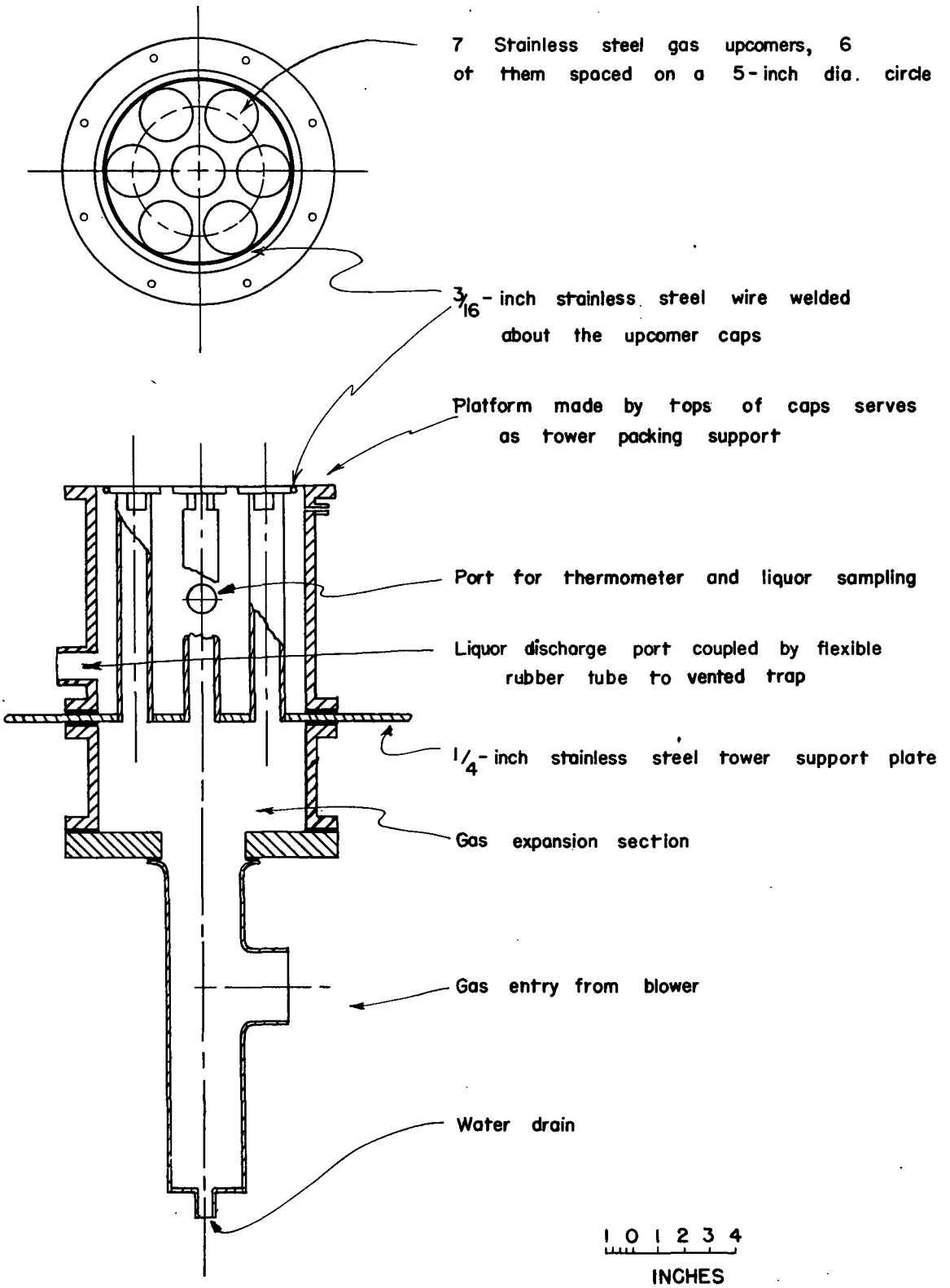


FIGURE 33. Absorption Tower Details: Gas Upcomer Section

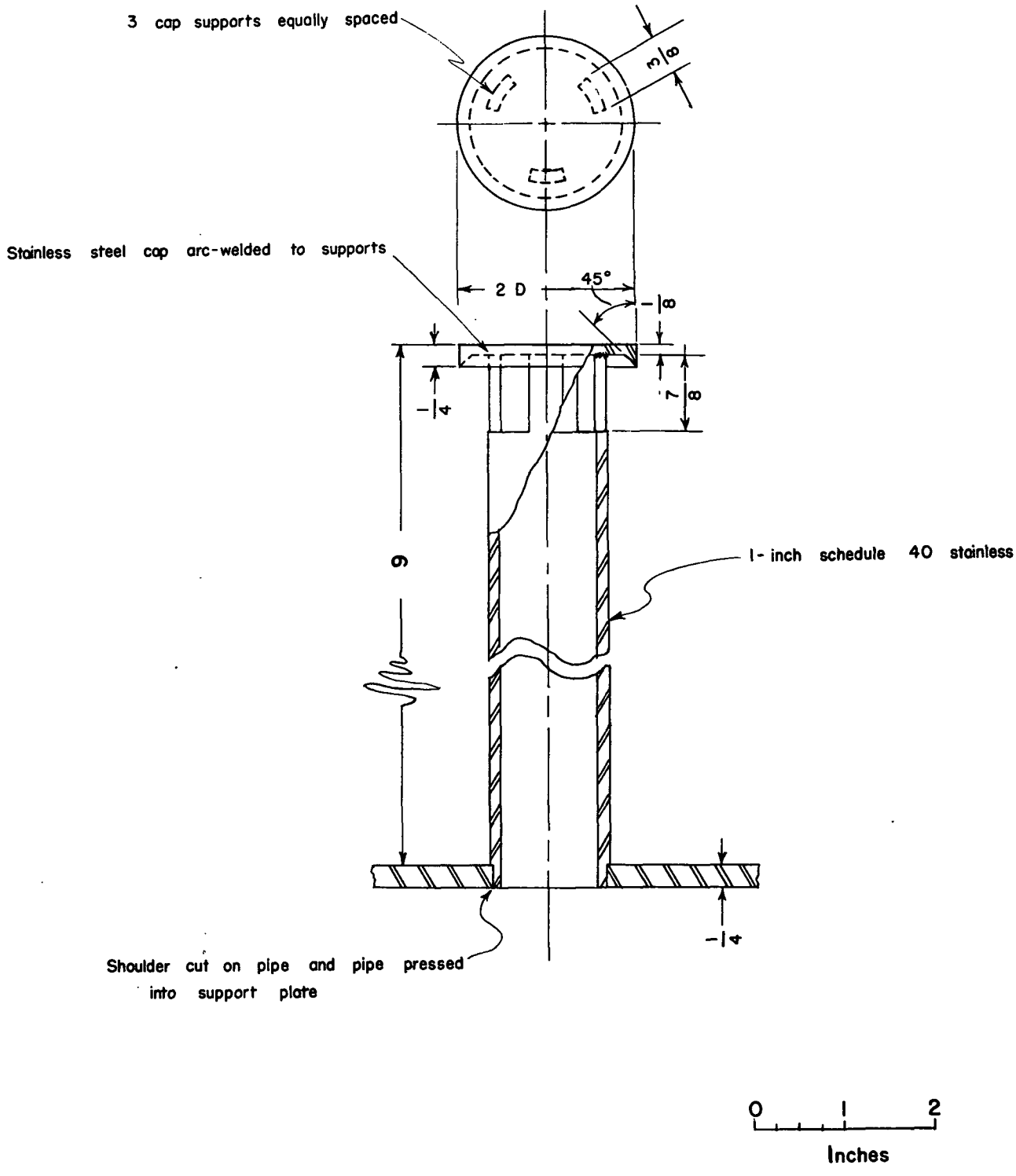


Figure 34. Absorption Tower Details. Gas Upcomer Details.

The top plate of the tower has an opening for the temperature regulator and thermometer both of which extend into the pool of liquor held by the weir. The liquor distribution section is internally vented to assure smooth liquor flow.

The gas expansion section is the gas space immediately above the top of the tower packing. The liquor downcomers pass through this section. A static pressure port is provided for indicating the tower pressure above the bed.

The packed section consists of flanged tubes bolted together to give the desired height of tower packing. Sections are six, nine, and twelve inches long; any tower height can be achieved up to 45 inches—in increments of three inches.

The packing consists of one-inch diameter ceramic Raschig rings, water dumped, and consolidated by vigorous hammering on the tower support. These rings have about 79% void volume and number about 1350 per cubic foot.

The gas upcomer section at the base of the tower has three sub-sections: (1) liquor pool, (2) gas expansion section, and (3) gas entry section. The liquor pool lies above and the gas entry and expansion sections below the 1/4-inch stainless steel tower support plate. The entire weight of the tower is borne by this plate.

Pressed into the support plate are seven gas upcomers which pass through the liquor pool and have caps over their slotted openings. These gas upcomers serve to support the tower packing and permit gas to be introduced to the packed section and at the same time prevent the flowing liquor from entering the gas expansion or entry spaces.

In addition to a static gas pressure port, the liquor pool section has a port for temperature measurement and sampling and a liquor discharge port. The liquor discharge port connects with a vented trap which has swivel joints permitting the trap to be pivoted and thus control the height of the liquor in the liquor pool section. This adjustment allows operating the tower with the liquor pool surface at a constant distance below the packed section.

The gas entry section is made of 13-gage, 3-inch welded stainless steel tubing and has a water drain at the bottom.

C. THE GAS SUPPLY SYSTEM

The gas supply system comprises (1) the closed circuits of stainless steel gas tubing, (2) gas blower and flow controller, (3) sulfur dioxide and nitrogen gas handling, metering, and inlet equipment, and (4) gas analyzer.

The gas tubing is a closed loop of 13-gage, 3-inch stainless steel tubing. The gas blower is a Clarage C1 exhauster having a 9 1/8-inch

diameter impeller balanced for 5400 r.p.m. The blower casing is cast iron covered with Heresite baked on.

The blower, as received, was modified by equipping it with a refrigeration-type rotary seal having a lapped brass and steel seal. Lubrication of the seal is provided by means of an oil dropper.

The blower is run by a U.S. Varidrive and can be operated over the range of 1600 to 5000 r.p.m. A butterfly damper at the tower entrance provides an additional means of controlling flow rates.

Cylinders of sulfur dioxide are immersed in a constant temperature water bath maintained at 100°F. (or above) which serves as an evaporator. The gas flows through a rotameter and enters the gas run ahead of the blower. Adjustment of sulfur dioxide input is determined by the gas analyzer on the input side.

A 23-ml. liquor sampler installed on the outlet side of the tower permits liquor samples to be drawn for analysis.

The gas flow rate is measured by means of square-edged orifice plates. Three orifices are used, depending on the range, their diameters being 1.40, 0.91, and 0.50 inches. The calibration curves for these orifices are given in APPENDIX V. A two-liquid differential manometer of amplification of approximately four was used.

All controls, except the liquor recycle throttle, are operable from a central position at the control board, and all indicators are located on the control panel. The absorption system is designed for one-man operation.

APPENDIX III

ANALYTICAL PROCEDURES: CHEMICAL METHODS

Iodimetry serves as the basis for chemical analysis for the entire thesis. The primary standard in this thesis is analytical reagent grade potassium iodate recrystallized four times from redistilled water (alkaline permanganate) and dried under vacuum for 24 hours at 120°C.

The chemical methods are involved in three kinds of determination, which are: (1) determination of sulfur dioxide or sulfite, (2) determination of sulfuric acid, and (3) the estimation of total dissolved oxygen in water.

A. DETERMINATION OF SULFITE AND SULFUR DIOXIDE BY IODATE IODIMETRY

1. THEORETICAL CONSIDERATIONS

The employment of potassium iodate, instead of iodine solutions as a source of iodine, avoids the usual troubles arising from its volatility. Potassium iodate affords a stable form of readily obtainable iodine for the oxidation of sulfite ion.

Landolt and others (59) studied the kinetics of the reactions between iodate and sulfite and reported the following reaction:

$$3SO_3^{=} + 3I_2 + 3H_2O \longrightarrow 3SO_4^{=} + 6H^{+} + 6I^{-}$$

The use of acidified iodate solutions is therefore virtually the same as the use of iodine solutions.

Hendrixson (60) showed that the reactions are quantitative, and he also ascertained that a potassium iodate solution maintains its concentration indefinitely when protected from evaporation and contamination.

Palmrose (61) developed a method for determining "free" and "combined" sulfur dioxide in lime-base solutions by means of a two-step titration on a single sample. White (62) employed a "modified" Palmrose method in which an excess of iodate is used and this excess back-titrated with standard thiosulfate. This modification is necessary wherever the titration must be carried out in a closed vessel. This modified method is the one employed in this thesis.

2. CHEMICAL ANALYSIS OF GAS MIXTURES CONTAINING SULFUR DIOXIDE

An investigation was made of several chemical and physical methods for the accurate determination of sulfur dioxide in gas mixtures where the content of sulfur dioxide is below one per cent by volume. Iodimetry proved to be the most accurate and reliable.

One-liter gas weighing balloons are used for sampling and for the analytical reactions. One liter of gas sample weighs from 1.00 to 1.30 grams so that samples are easily weighed to four significant figures.

Because of the size of the balloons it is necessary to use a Christian-Becker 2000-gram capacity balance having long beams and sufficient room on the pans to receive the weighing balloons. The balance is accurate to 0.2 milligram and weighing by deflection was resorted to in order to speed weighings.

The balloons were modified by securely sealing the ground joint with General Electric Glyptal varnish to insure against leakage and the chance that the ground joint might be forced out by any increase in gas pressure within the balloon.

The gas sample was collected in the evacuated, dry, and previously weighed balloon and the sample weight determined by difference. Ten milliliters of 7 N sulfuric acid and 10 milliliters of 10% potassium iodide were added from a pipet attached to the weighing balloon by means of a short length of rubber tubing. The flask and contents were reweighed and potassium iodate solution added to the first permanent straw color. The strength of iodate was chosen such that 10-30 ml. of solution were sufficient for a titration. Iodate solutions containing 0.003000, 0.01750, and 0.04000 meq./g. serve satisfactorily.

Back titration of the excess iodate was accomplished with 0.0010 to 0.0025 N sodium thiosulfate solution. The thio solution must be restandardized for every set of analyses. The volume of thio required

for back titration of the iodate was in the range of 4-12 ml., and this same range was held to in the standardization.

3. CHEMICAL ANALYSIS OF SOLUTIONS CONTAINING SULFUR DIOXIDE

The analysis of solutions containing sulfur dioxide follows the same general procedure as that for analyzing gases. Two-hundred milliliter balloons were used instead of the liter size.

A departure was made in the determination of sample size of liquor samples from the tower. Samples were drawn from a 23-ml. sampling pipet and not weighed. Also, the amount of iodate solution added was measured by the volume delivered from a buret instead of weighing the balloon and contents. Titrating in this manner resulted in a saving of time with no significant reduction in accuracy.

B. ANALYSIS OF TOWER GAS SAMPLES BY MEANS OF VOLUMETRIC METHOD

Neither volumetric analysis of gas samples, involving the weighing of samples, nor ultraviolet absorption analysis (discussed in APPENDIX IV) are entirely free of difficulties and uncertainties. It seemed advisable to work out an additional method of analysis which could be used to check gross errors of the other two methods. The method resulted in a simple analytical means having sufficient accuracy yet free of some of the uncertainties which diminish the usefulness of the other methods.

1. METHOD OF ANALYSIS

The volumetric method involves drawing a sample of saturated gas into a dry, evacuated gas balloon, the volume of which is accurately known. The contents are then titrated in the usual way and the number of milliequivalents of sulfur dioxide computed. A multiplying factor is used to convert the milliequivalents of sulfur dioxide to partial pressure of the gas.

2. DERIVATION OF MULTIPLYING FACTOR

If the number of gram-mols of sulfur dioxide in a sample is computed as

$$\text{g-mols } SO_2 = (\underline{meq})_b \times 0.001/2 = 0.0005\ (\underline{meq})_b \qquad (31)$$

and the mol-volume of the sampling balloon is computed as

$$\text{Moles} = \underline{P}_t\ \underline{V}_b / \underline{R}_b\ \underline{T}_b \qquad (32)$$

then the mol-fraction of sulfur dioxide in the sample is

$$\underline{x}_{SO_2} = 0.0005(\underline{meq})_b \times \underline{R}_b\ \underline{T}_b / \underline{P}_t\ \underline{V}_b \qquad (33)$$

and conversion of the mol-fraction to partial pressure is accomplished by multiplying by the total pressure.

$$\underline{p}_{SO_2} = \underline{P}_t \times 0.0005\ \underline{R}_b / \underline{V}_b\ \underline{P}_t \times (\underline{meq})_b \times \underline{T}_t \qquad (34)$$

The pressure terms cancel out and an expression for the multiplying factor $\underset{\sim}{f}_b$ may be written as

$$\underset{\sim}{f}_b = 0.0005 \times \underset{\sim}{R}_b / \underset{\sim}{V}_b \times \underset{\sim}{T}_b \qquad (35)$$

The factor is a function of the weighing balloon volume and temperature and must be computed for each balloon used.

C. THE STANDARDIZATION OF SULFURIC ACID SOLUTIONS BY MEANS OF IODIMETRY

Potassium iodate is used for the standardization and analysis of sulfuric acid solutions. The method employed is discussed fully by Kolthoff and Sandell (63). Briefly, the principle involved is the reaction between iodate, iodide, and hydrogen ions to produce elemental iodine according to the equation:

$$IO_3^- + 5I^- + 6H^+ \longrightarrow 3I_2 + 3H_2O$$

A neutral iodate solution is used which contains an excess of iodide and thiosulfate; as acid is added, the hydrogen ions are removed to produce iodine which, in turn, reacts with the thiosulfate:

$$I_2 + 2S_2O_3 \longrightarrow 2I^- + S_4O_6^=$$

The tetrathionate is colorless, and the solution remains neutral until all iodate is used up. An excess of acid is indicated by methyl red indicator.

Precautions to be observed are (1) avoiding too large an excess of thiosulfate, (2) allowing sufficient time for the indicator color to develop toward the end point, and (3) carrying out the titration under a good, uniform source of white light.

D. THE DETERMINATION OF TOTAL OXYGEN CONTENT OF WATER

The volumetric method for oxygen analysis adopted here is that of Winkler (64). The principle involved is that of oxidizing manganous hydroxide to manganic acid which, in turn, is reduced to manganous ion and simultaneously oxidizes iodide ion to elemental iodine which is then titrated with standard thiosulfate. The equations are as follows:

(1) $MnSO_4 + 2NaOH \longrightarrow Mn(OH)_2 + Na_2SO_4$

(2) $Mn(OH)_2 + 1/2\ O_2 \longrightarrow H_2MnO_3$

(3) $H_2MnO_3 + 2H_2SO_4 + 2KI \longrightarrow MnSO_4 + 3H_2O + K_2SO_4 + I_2$

Samples are taken in clean, dry, glass-stoppered bottles of approximately 273 ml. volume. The bottles are filled to overflowing and tightly stoppered. The reagent solutions are then added in the order (1) manganous sulfate, (2) alkaline potassium iodide, and (3) concentrated sulfuric acid. Two milliliters of each solution are

added and the bottle shaken after each addition. Two hundred and fifty milliliters are then drawn for titration with thiosulfate. The strength of thiosulfate solution is about 0.007 N which represents approximately 4.52×10^{-7} lb.-mols of oxygen per cubic foot per milliliter of this used with a 250-ml. sample.

APPENDIX IV

ANALYTICAL PROCEDURES: ULTRAVIOLET ABSORPTION GAS ANALYSIS

A. OPERATING PRINCIPLE

The successful employment of an ultraviolet photometer for analyzing ozone content of air (66) suggests the possibility of employing ultraviolet absorption as a means of determining sulfur dioxide concentration in gases. Such a method would be of advantage in the analysis of the tower feed and exit gases since the method is instantaneous, continuous, and requires no samples to be drawn and therefore avoids upsetting the conditions in the closed-cycle system.

Varley (67) mentions that sulfur dioxide shows a strong absorption between 262.0 and 317.9 mmu and a feeble one between 230 and 344 mmu. LeBlanc (68) found a maximum at 290 and a minimum at 240.

A preliminary investigation of the ultraviolet absorption characteristics of sulfur dioxide was carried out in a quartz cell examined in the Beckman spectrophotometer. The absorption curve obtained is shown in Figure 35. The maximum extinction coefficient at 287 mmu is approximately six. The spectral energy characteristics of the Uviarc quartz tube mercury vapor lamp are superimposed on the absorption curve. The mercury vapor lamp spectral output data are those of Hughes and Du Bridge (70). The ordinate of the strong 253.7 mmu line is taken as unity.

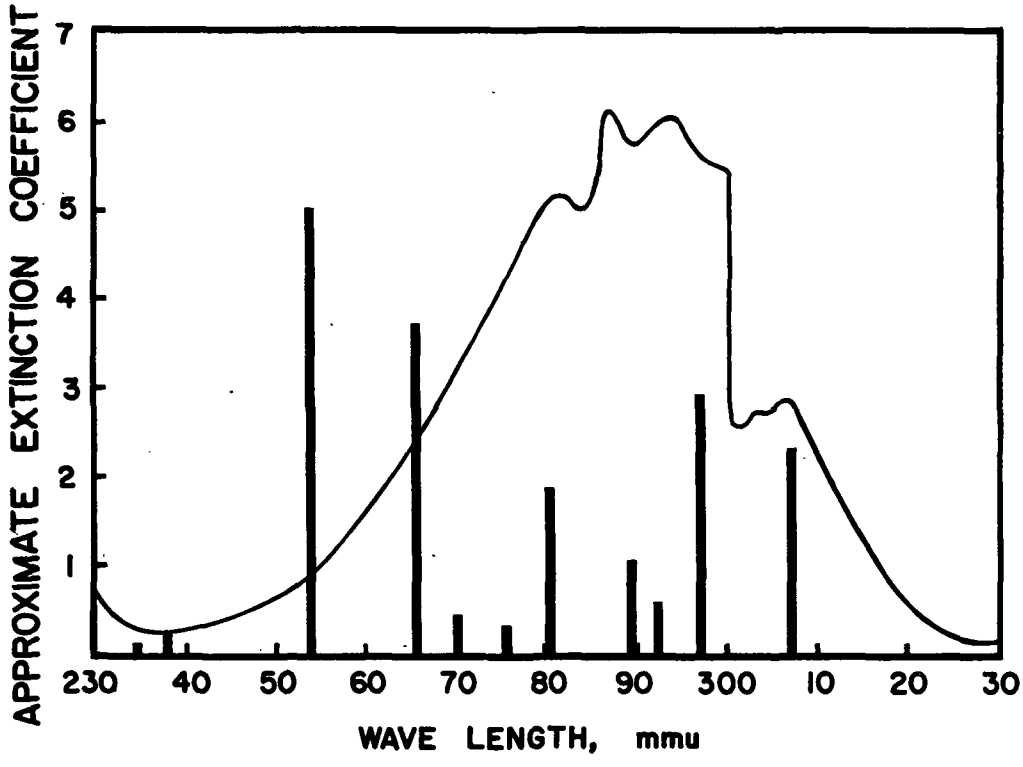


Figure 35. Comparison of the Spectral Band Intensities of the Uviarc Quartz Mercury Vapor Lamp and the Extinction Coefficient for Sulfur Dioxide.

The operating principle of this analytical method is the same as that used by Van den Akker for ozone analysis (66). Ultraviolet light passes through a length of gas, the emergent beam striking a glass plate with a suitable phosphor coating. The residual ultraviolet in the beam causes the phosphor to fluoresce and this fluorescence is picked up by a photocell. A suitable filter is included ahead of the photocell to remove any remaining ultraviolet unconverted by the phosphor and blue, green, and yellow light of wavelength less than 580 mmu. Figure 36 shows the constructional elements making up a gas analysis cell.

The phosphor is cadmium borate* which gives a red-orange fluorescence when excited by ultraviolet below 280 mmu. The wavelength of maximum spectral energy of the fluorescent light is 615 mmu. (71).

The phosphors are prepared by coating the cadmium borate on 1.5-mm. photographic glass plates, a coating weight of 4.58 milligrams per square centimeter being used. The coating is applied by sedimentation of the cadmium borate from a suspension in 5% ethyl cellulose in ethyl alcohol-benzene (2:1) mixture. The solution contains 10% dimethyl phthalate (based on ethyl cellulose) as a film plasticizer.

The sedimentation is carried out in a crystallizing dish and after 8-24 hours the supernatant liquor is drawn off and the coating permitted to dry thoroughly. The phosphor disc is very slowly brought to a dull red heat in a muffle furnace and then allowed to cool. Baking the

*Furnished by General Electric, Nela Park.

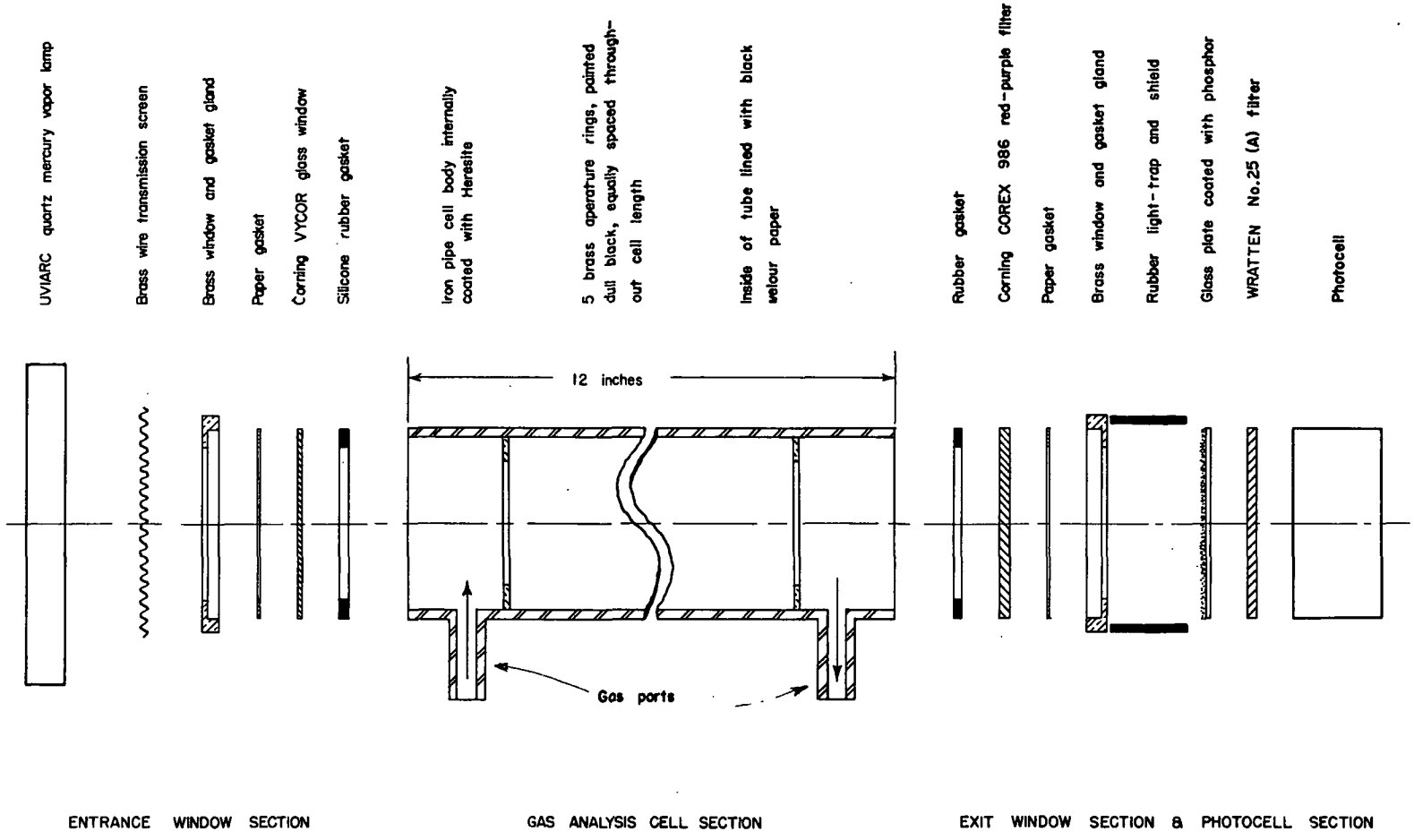


Figure 36. Constructional Elements of the Ultraviolet Absorption Gas—Analysis Cell.

phosphor removes the film material and leaves the cadmium borate as a thin, uniform, white coating on the glass. The coating is fragile and must be handled with care.

The output of the Uviarc lamp fluctuates and these fluctuations are not removed by operating the lamp on a constant voltage source (1-Kv Sorensen Voltage Regulator). In order to avoid these troubles, a null system was adopted which depends on the bucking of two photocells in a bridge circuit (Figure 37).

The two photocells, active (A) and dummy (D), are respectively Weston and General Electric blocking-layer cells chosen because the two cells showed the best match in operating characteristics among the cells available. The active cell views the ultraviolet through any one of three identical analysis cells—feed gas, exit gas, and comparison, mounted on a sector which pivots the cells about a common axis. The cells may thus be switched to allow analysis of either feed or exit gas. The comparison cell allows resetting the instrument index.

Between the lamp and the cells is a slide carrying two standard screens of 37.5 and 62.5% transmission, as well as a clear opening. These screens serve the purpose of reference transmission values and, in conjunction with the comparison cell, provide a means of resetting the instrument index. The dummy cell, located below the active, has superimposed in the light path a wedge opening which may be operated

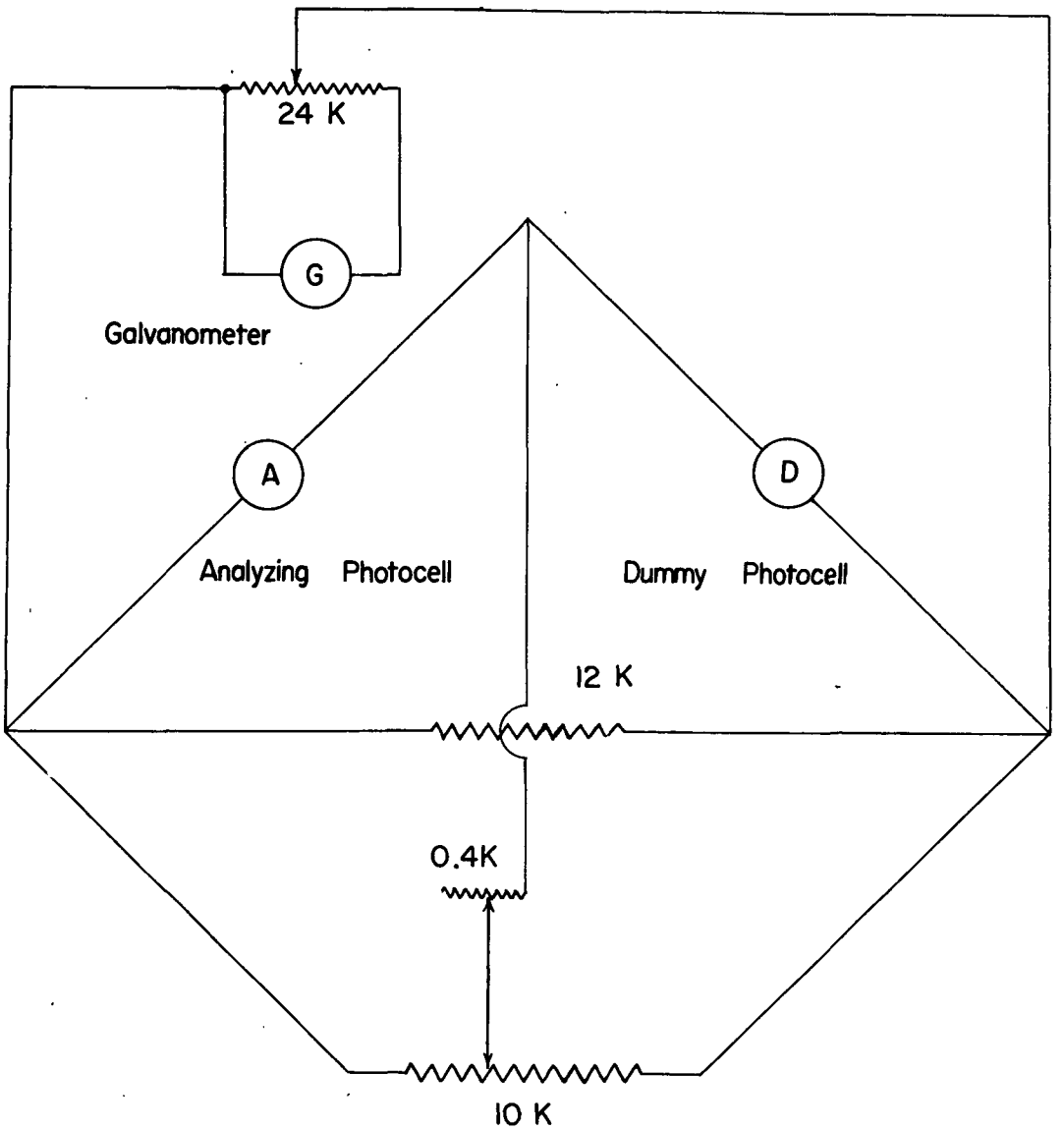


FIGURE **37.** Electrical Bridge Circuit for Gas-Analysis Instrument.

from side to side to vary the light reaching the cell. Figure 38 shows the arrangement of the lamp, analysis cells, and the sliding wedge and screens.

The operating principle of the instrument is the balancing of the bridge circuit by operating a wedge opening in front of the dummy cell until the light intensities of the analysis cell and the dummy cell are equivalent; the wedge setting is then read from a millimeter scale. A galvanometer indicates the balance.

The galvanometer used is a Leeds and Northrup d'Arsonval Type R, Serial 219118.* The galvanometer deflections are indicated by means of a light source and plane mirror optical lever shown in Figure 39. The length of the lever in conjunction with the galvanometer sensitivity results in an extremely sensitive balance indicator.

The steps involved in making an analysis of the tower feed or exit gas are as follows: The lamp must be at operating temperature and the galvanometer mechanical zero should be adjusted to fall at approximately the midpoint of the one-meter transparent scale. The Ayrton shunt is kept at zero to provide protection for the galvanometer. The comparison cell is swung into position and the wedge on the dummy adjusted to the proper reference mark. The transmission screen corresponding to the wedge setting is slid into place and the indicator adjusted to zero by balancing the bridge. As the balance point is approached, the

*Sensitivity 10,100 mm./μA, C.D.R. x 24K ohms, Resistance 595 ohms, period 14.8 sec.

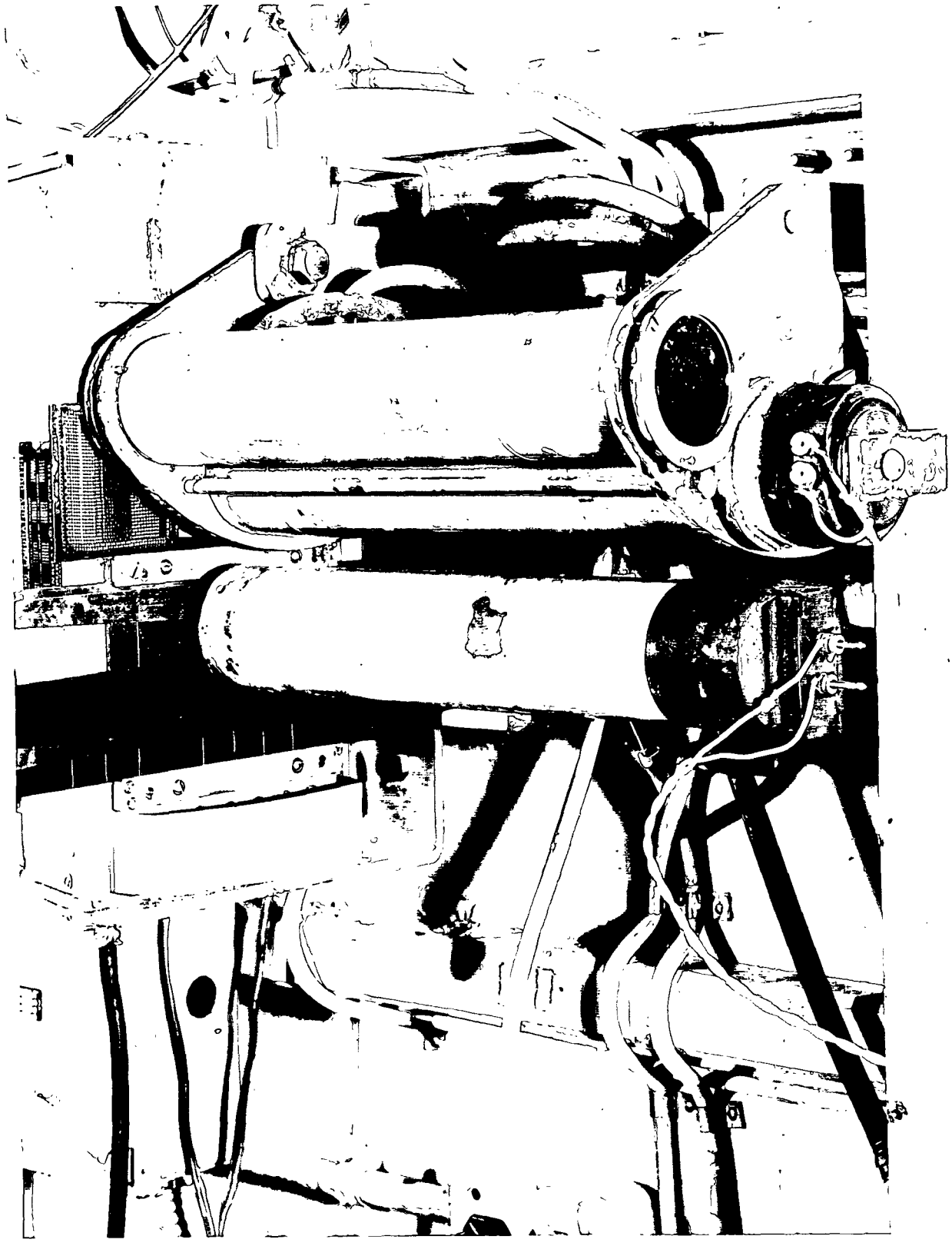


Figure 38. Close-Up of Ultraviolet Absorption Gas-Analysis Unit.

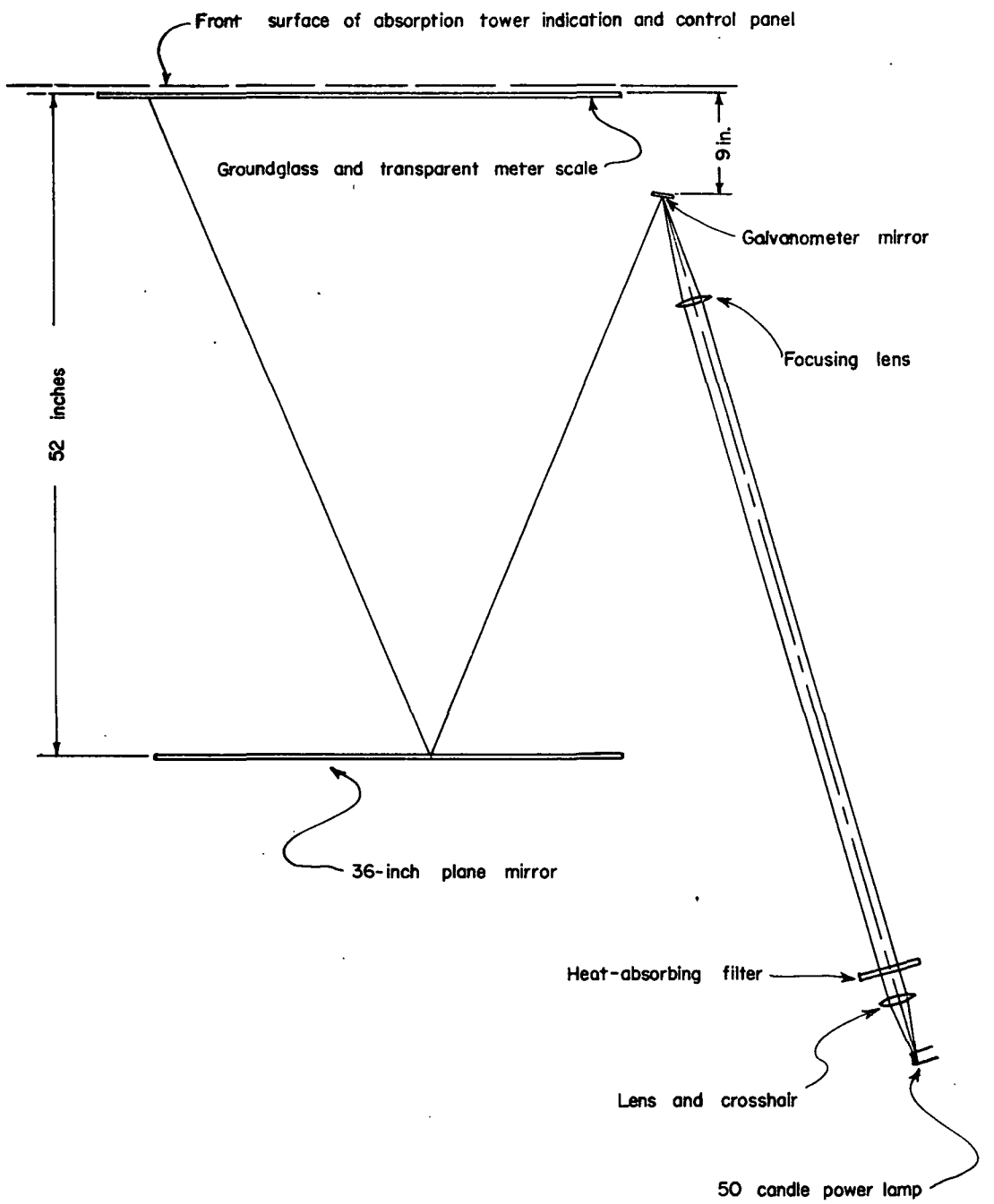


FIGURE 39. Gas-Analysis Instrument Optical Lever

galvanometer shunt is adjusted to give increased sensitivity. The feed gas or exit gas cell is switched in, the transmission screen removed, and the wedge on the dummy operated until a balance is obtained. The scale reading on the wedge then may be converted to sulfur dioxide concentration by means of a calibration curve.

An example will make these steps clearer. Suppose the index value is 14*, then the instrument is zeroed by setting the wedge scale at a reading of 14.0 cm., the 37.5% transmission screen is moved in front of the analysis cell, and the coarse and fine resistances adjusted until the indicator comes to a balance reading corresponding to the mechanical balance point of the galvanometer. The analysis of a gas sample is then accomplished by taking the 37.5% transmission screen out of the light path (allowing 100% transmission), switching in the appropriate gas-analysis cell, and operating the wedge until a balance is made. The scale value is then read. The zero point is rechecked before each analysis.

Gas is brought into the cell by means of a hand squeeze bulb which is pumped 17-20 times, or until a constant reading is obtained. The temperature and pressure of the gas are noted since they are necessary for converting the analysis data to gas partial pressure.

*The index value is established at the time the analysis cell is calibrated.

The nominal range of sulfur dioxide concentration which may be analyzed corresponds to approximately 0.0300 - 1.50% sulfur dioxide by volume. This analysis range may be changed by either altering the wedge opening or by changing the index adjustment. Making the ratio of the wedge width smaller reduces the analysis range (compresses it), and changing the index results in a lateral shift in the analysis range—a lower index number shifts the analysis range to higher values.

The analysis range of the cell is also determined by cell length and construction variables. The cell length adopted for this thesis is 12 inches. A comparison of the performance of 12- and 24-inch cells is shown in Figure 40.

B. CALIBRATION OF THE GAS ANALYZER

Calibration of the gas analyzer was accomplished by operating the tower with a continuous feed of nitrogen so that some tower gas was continually bled at the rotary seal. The tower was allowed to run at least ten minutes in order to attain a steady-state condition before analysis-cell readings were taken. A sample of gas was then drawn and analyzed. The feed and exit analysis cells were connected in series during the calibration in order that one gas analysis would suffice for both cells. The tower operating temperature was varied as a check

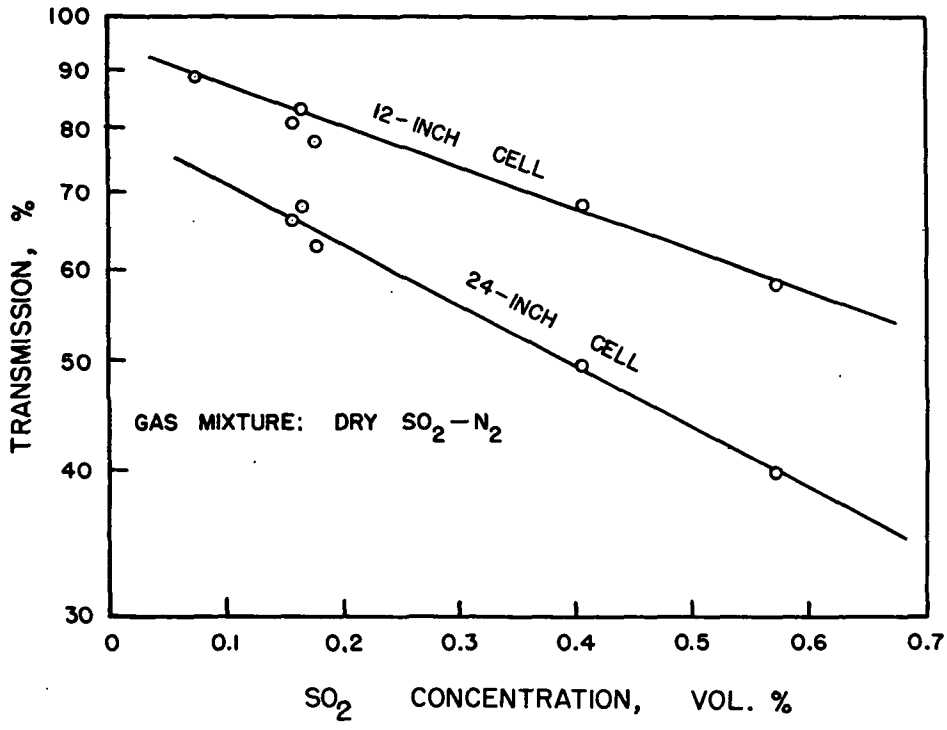


FIGURE 40. Comparison of 12 and 24-inch Analyzer Cells.

on the efficiency of the gas drying train. Also a series of calibration runs was made in which prepared dry nitrogen-sulfur dioxide mixtures were employed.

The calibration chart resulting from these trials is shown in Figure 41. The values determined by the analyzer are pounds of sulfur dioxide per cubic foot of gas in the analyzer at the conditions of temperature and pressure extent at the time of analysis.

C. SOURCES OF VARIANCE AND ERROR IN THE INSTRUMENT

When the original decision was made to investigate the use of ultraviolet absorption as a means of gas analysis, it was also decided to keep the electrical circuit as simple as possible and thus avoid the problem of working out a vacuum tube circuit. Compactness and portability were of no importance, and it was originally planned to design the instrument in such manner as to make it direct reading.

The final instrument has thus required certain compromises, and it is felt that a full discussion of the sources of variance in the instrument's operation is therefore appropriate. The analysis principle is sound, and it is the author's conviction that a better designed and constructed unit would possess excellent accuracy, surpassing the estimated 2%* of the present one.

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*Two per cent of the determined value.

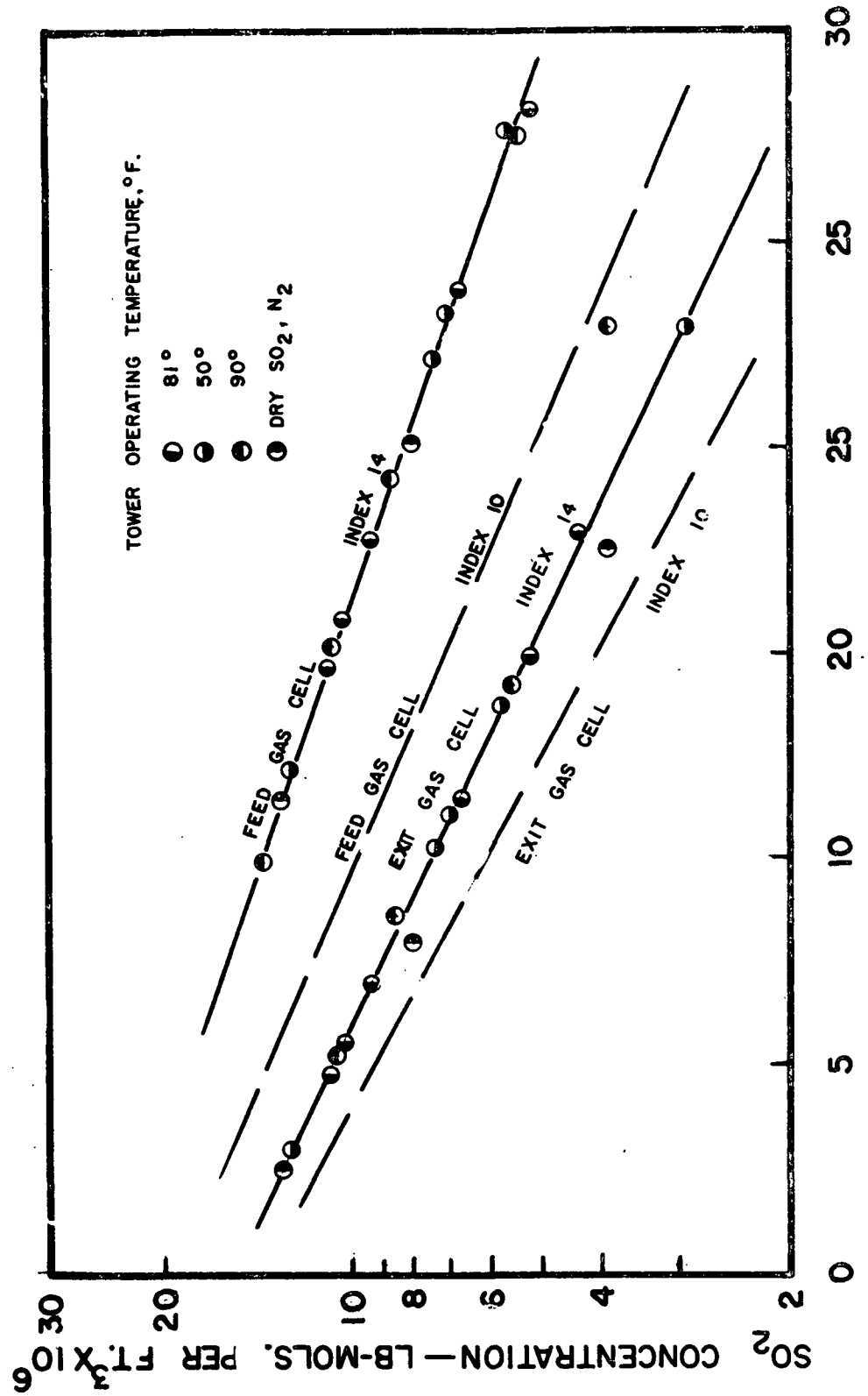

FIGURE 41. Calibration of the Ultraviolet Absorption Gas Analyzer.

The nature of this instrument suggests possibilities for use in continuous indication and control applications.

TABLE XXI

CALIBRATION OF ULTRAVIOLET ABSORPTION GAS ANALYSIS CELLS

(Figure 41)

Gas Saturation, Temp. °F.	SO_2 Conc., at Cell Conditions, lb-mols/ft.^{3} x10^6	Analyzer Scale Reading Feed Cell	Exit Cell
50	2.87	---	22.85
50	5.62	27.62	13.70
50	6.82	23.20	11.00
50	7.28	22.10	10.20
50	12.40	12.10	2.90
81	4.13	32.70	17.85
81	5.10	28.82	14.95
81	6.61	23.87	11.40
81	9.28	17.70	6.95
81	10.20	15.80	5.47
81	10.80	14.65	4.70
90	3.81	---	23.07
90	5.43	27.60	14.15
90	8.53	19.15	8.53
90	10.50	15.20	5.15
90	13.93	9.90	---
Dry (55)*	3.84	---	17.50
Dry (56)	7.88	20.00	7.85
Dry (57)	12.90	11.40	2.40

*Numbers in parentheses refer to gas mixture numbers.

Sources of variance in the instrument, which manifest themselves in unsteadiness and wandering of the indicator on the balance scale, originate in the (1) lamp, (2) photocells and electrical circuit, and (3) the analysis cells and cell assembly.

1. ANALYZER VARIANCE DUE TO THE LAMP

The Uviarc lamp consists of a quartz mercury vapor tube and a polarized reactance. The arc in the tube exhibits unsteadiness and wandering and the light output is neither constant nor uniform over the length of the tube. The lamp output is also dependent on line voltage fluctuations and frequency changes. A voltage regulator helps to reduce troubles due to varying voltage but will not entirely remove them.

The lamp must be allowed to come to operating temperature before the analyzer is operated and must be protected from cold drafts, but at the same time consideration must be given to proper ventilation of the lamp.

2. VARIANCE DUE TO THE PHOTOCELLS AND ELECTRICAL CIRCUIT

The bridge circuit arrangement makes the resistance properties of the photocells important and causes the circuit to become sensitive to differences in temperature at the photocells. This difficulty was

overcome by playing a current of air from a fan placed about 5 feet distant. The circulating air keeps the analyzer assembly at essentially uniform temperature.

The moving air also aids in eliminating transient temperature differences which otherwise can cause troubles through the generation of thermal electricity at junctions having different temperatures.

3. VARIANCE DUE TO THE ANALYSIS CELL AND CELL ASSEMBLY

Light leaks, gas leaks, and dirty or dusty cell windows may contribute to analysis error. The sliding wedge must consist of blades which have been accurately ground and have no local unevenness, burrs, or tool marks. The entire wedge assembly must be made of the same composition metal or eccentricities due to thermal expansion may develop. In the present instrument the wedge is of cold-rolled steel and the edges are ground flat to within less than 0.001 inch.

Insufficient sweeping of the cell by the gas sample is cause for error, but this is easily avoided by pumping gas in until the indicator reaches a steady balance point. In fact, two of the most serious sources of error can be in condensation (or fogging) of moisture from the gas while inside the analysis cell and failure of the gas to come to a known temperature within the cell.

Fogging and other troubles due to water vapor in the gas are avoided by drying the gas through a bed of Drierite (calcium sulfate). The gas sampling and analysis train is shown in Figure 42. Caution must be exercised to assure passing the wet gas sample through the Drierite bed at a rate low enough to allow efficient desiccation. The total void volume of the gas train is approximately 1200 cc. and thus requires operating the bulb 17-20 times. The Drierite is regenerated at the end of each day by running hot, dry air through the bed for several hours (overnight).

The temperature of gas was determined by means of a thermometer attached to the outside surface of one of the cells and the gas sample allowed to remain in the cell for a sufficient time to reach thermal equilibrium. Tempering of the gas was also partly accomplished during its passage through the four feet of 1/4-inch copper tempering coil ahead of the entrainment trap.

Gas pressure in the cell is indicated by means of a manometer.

Although the ultraviolet absorption method was proved to be practical and of sufficient accuracy, certain over-riding considerations forced the abandonment of its use for analysis of the tower feed and exit gases. Although the cell operates instantly, time is required to flush the cell and system and to pump a gas sample into the cell for tempering. The time for these operations required several minutes,

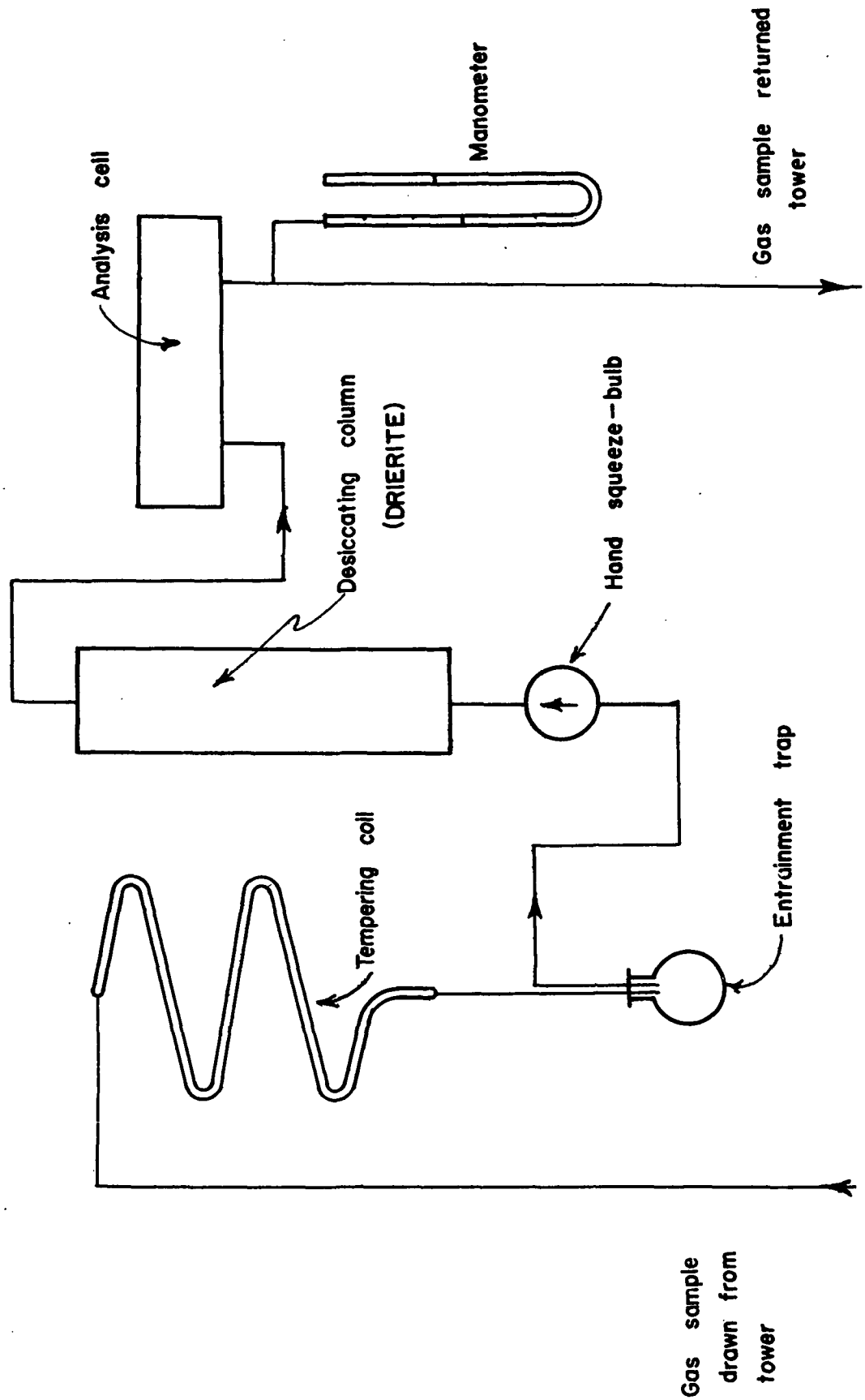

Figure 42. Gas Analyzer Sample Train.

which proved prohibitively long. The instrument was used, however, as a concentration level indicator and permitted reasonably accurate control of the sulfur dioxide input to the tower system.

APPENDIX V

SAMPLE CALCULATIONS AND CALIBRATION CURVES

A. CALCULATION OF OXYGEN DESORPTION DATA

Example: Oxygen desorption Run No. 89

1. STANDARDIZATION OF THIOSULFATE SOLUTION.

Barometric pressure, cm. Hg	73.94
atm.	0.983
Temperature of air-saturated water, °F.	69.0
Time air bubbled through water, hr.	36
Volume of ground-glass stoppered sample bottle, ml.	279
Volume of sample analyzed, ml.*	250
Reagent solutions added to ground-glass stoppered sample bottle, ml.	
Solution No. 1 (contains 480g. $MnSO_4$/liter of H_2O)	2
Solution No. 2 (contains 360g. NaOH, 100g. KI per liter of H_2O)	2
Solution No. 3 (contains conc. H_2SO_4)	2
Thio titre, ml.	37.70
H constant (Figure 43), lb.-mols x 10^5/ft.^{3} atm.	8.56

*Samples are of constant volume—250 ml. in all cases.

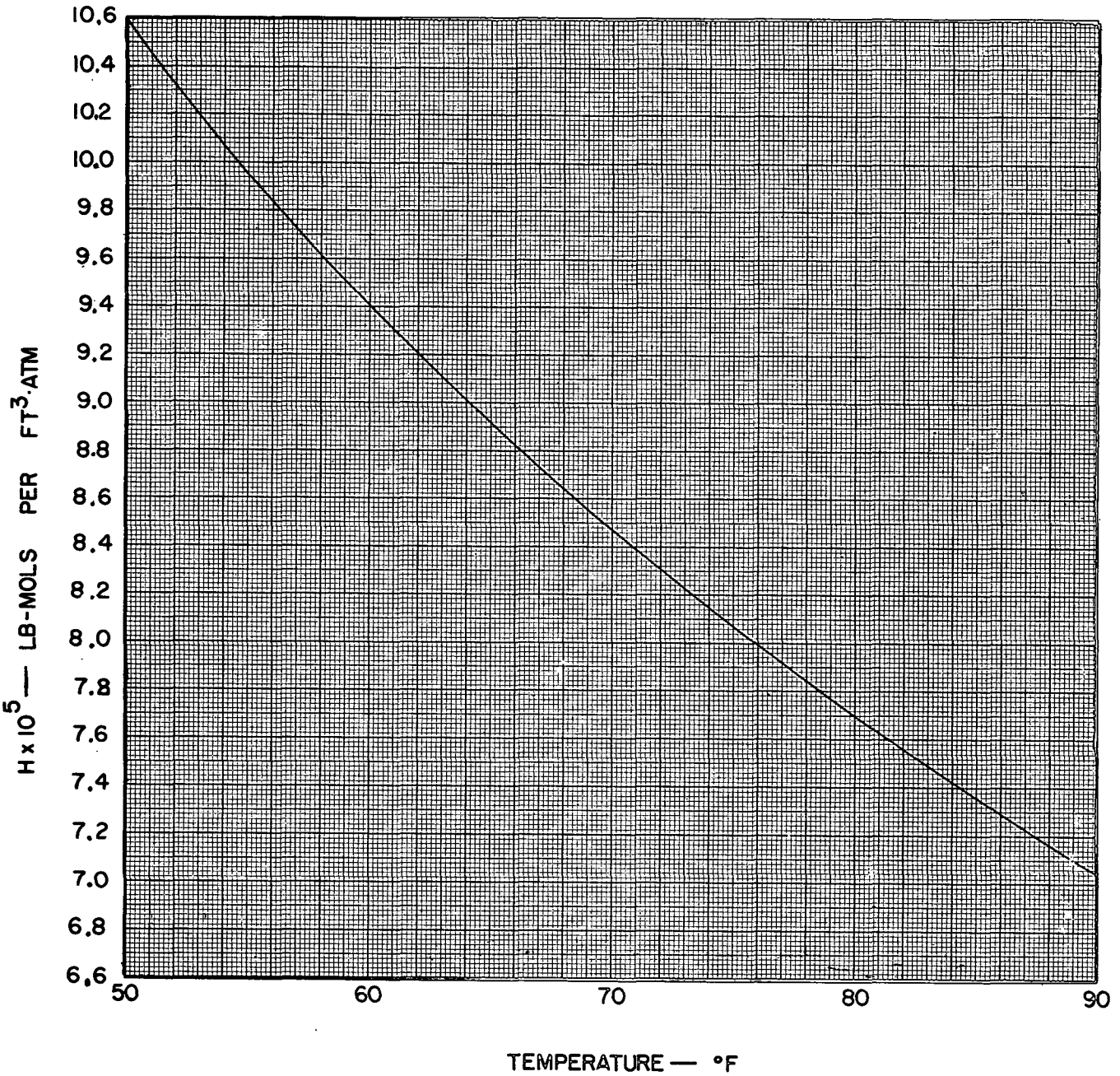

FIGURE **43.** Henry's Law Constants for the System Oxygen-Water. From the data of Winkler (64).

Partial pressure of oxygen in saturating air*, atm.

Barometric pressures, atm.	0.973	
Partial pressure of water vapor	0.025	
Partial pressure N_2-O_2	0.948	
Partial pressure of oxygen,	0.948 x 0.210	0.199

Concentration of oxygen in saturated water. lb.-mols $\times 10^5$/ft.^{3}

$0.199 \times 8.56 \times 10^{-5}$	1.70
Thio factor, lb.-mols x 10^7/ft.^{3} ml.	4.52

2. TOWER RUN DATA

Temperatures

Liquor in, °F.	80.0
Liquor out, °F.	80.0
Gas in, °F.	82.0
Gas out, °F.	80.0

Liquor flow rate

Water collected in pail, g.	8286
Collection time, sec.	57.2
Inlet liquor thio titre, ml.	84.6
Outlet liquor thio titre, ml.	40.7

Gas flow rate

Orifice differential, cm.	8.60
Orifice pressure, cm. Hg	0.16
Barometric pressure, cm. Hg	73.75
atm.	0.970

*Compressed air from the service supply was used. The air was bubbled through water before going to saturator.

Tower packed height, ft. 2

Average tower pressure, cm. Hg 73.95

3. PHASE FLOW RATES

Gas orifice plate diameter, in. 0.50

Orifice pressure cm. Hg. 73.91
atm. 0.972

Partial pressure of water at 80.0°F., atm. 0.0345

Partial pressure of $N_2 - O_2$, atm. 0.938

Apparent molecular weight of gas

$0.938 \times 29.0/0.972 = 28.0$

$0.0345 \times 18.0/0.972 = \frac{0.639}{28.6}$

Density of gas, lb./ft.^{3}

$$\frac{28.6}{359} \times \frac{492}{540} \times \frac{0.972}{1.00} = 0.0705$$

Gas orifice differential, feet of flowing fluid

$$\frac{8.60}{30.48} \times 0.257 \times \frac{62.2}{0.0705} = 35.5$$

Volume of gas flowing (Figure 43), cu.ft./hr.ft.^{2} 570

Rate flow of inerts, lb./hr.ft.^{2}

$570 \times 0.0705 \times 28.0/28.6 = 40.2$

Water flow rate, lb./hr.ft.^{2}

8290/57.2 x 3600/454 x 9/π 3,290

4. DISSOLVED OXYGEN CONCENTRATION OF INLET AND OUTLET LIQUORS AND THE EQUILIBRIUM CONCENTRATION AND DRIVING FORCES OVER THE TOWER

Inlet liquor concentration, lb.-mols x10^5/cu.ft.

40.7 x 4.52 x 10^7 3.83

Outlet liquor concentration lb.-mols x10^5/cu.ft.

40.7 x 4.52 x 10^7 1.84

Average tower pressure, atm. 0.973

Oxygen partial pressure in tower, atm.

0.210 x 0.938 0.197

Henry's law constant for 80°F. (Figure 40)
lb.-mols x10^5/ft.^{3}atm. 7.70

Equilibrium solubility of oxygen in water,
lb.-mols x10^5/ft.^{3}

0.197 x 7.70 1.52

Concentration driving force, inlet side

Δc_2, lb.-mol x 10^5/ft.^{3}

3.83 - 1.52 2.31

Concentration driving force, outlet side, Δc_1, lb.-mol x10^5/ft.^{3}	
1.84 - 1.52	0.32

5. VALUE OF $K_L a$, HR.$^{-1}$

$$K_L a = L/\rho h \log_e \Delta c_2/\Delta c_1$$

$$= 3{,}290/(62.2 \times 2.15) \times 1.98$$

$$= 48.8$$

B. CALCULATION OF SULFUR DIOXIDE PARTIAL PRESSURE BY VOLUMETRIC METHOD

Example: Feed gas sample of sulfur dioxide absorption Run No. 269.

1. COMPUTATION OF MULTIPLYING FACTOR, f_b *

Gas constant, R_b, liter-atm./mol °R.	
1.000 x 22.41/1 x 491.4	0.0456
Volume of gas-weighing balloon, liter	1.003

Multiplying factor, f_b, $\frac{\text{atm.}}{°\text{R.}} - (\text{meq})_b$

$$0.0005 \times 0.04560/1.003 \times T_b = 2.273 \times 10^{-5} \times T_b$$

2. PARTIAL PRESSURE OF FEED GAS SAMPLE, ATM.

Analysis of gas sample	
Milliequivalents of iodate	0.4156
Milliequivalents of thio	0.0236
Milliequivalents of sulfur dioxide	0.3920

*The derivation of this factor is discussed in Section B, of APPENDIX III.

Temperature of gas sample, °F. 70.0

Partial pressure of feed gas, atm.

$$\underline{f}_b \times (\underline{meq})_b$$

$$2.273 \times 10^{-5} \times \underline{T}_b \times (\underline{meq})_b$$

$$2.273 \times 10^{-5} \times 529.4 \times 0.3920 = 0.004716$$

C. CALCULATION OF THE OVER-ALL SULFUR DIOXIDE ABSORPTION COEFFICIENT

The partial pressures of feed and exit gases for the low-concentration were obtained by means of the volumetric gas analysis. (See Figure 45 for data on the apparent molecular weight of sulfur dioxide.)

1. NORMAL COEFFICIENT--MEAN DRIVING FORCE BY INTEGRATION.

Example: Absorption Run No. 251

Temperature, °F.	70
Packed height, ft.	1
System	water
Liquor rate, $\underline{L}$, lb./hr.ft.^{3}	5,000
Gas rate, $\underline{G}$, lb./hr.ft.^{2}	91.5
Gas partial pressure, atm.	
Feed, $\underline{p}$	0.008730
Exit, $\underline{p}_2$	0.001499
Liquor concentration, lb.-mol/ft.^{3}	
Inlet, $\underline{c}_2$	0.0
Outlet, $\underline{c}_1$	0.000292

Material balance

$$\frac{\text{Moles lost by gas}}{\text{Moles gained by liquor}} \qquad 1.09$$

By inspection of the equilibrium curve of Figure 13, the curvature between p_1 and p_2 is too great to permit use of the log-mean driving force so the differential tower equation must be solved by integration.

$$\underline{K}_L \underline{a} = \underline{L}/\underline{h} \int_{\underline{c}_1}^{\underline{c}_2} d\underline{c}/\underline{c}_e - \underline{c}$$

The integration may be done most simply by means of Simpson's rule by dividing the operating diagram into eight panels in the manner shown in Figure 44.

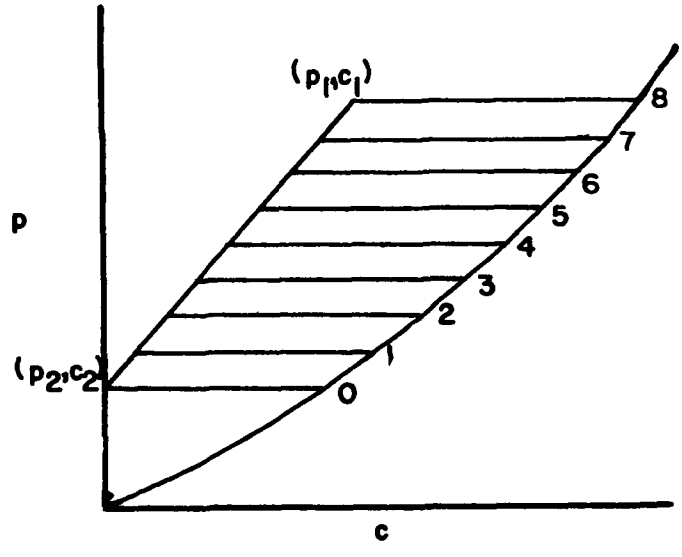

FIGURE 44.

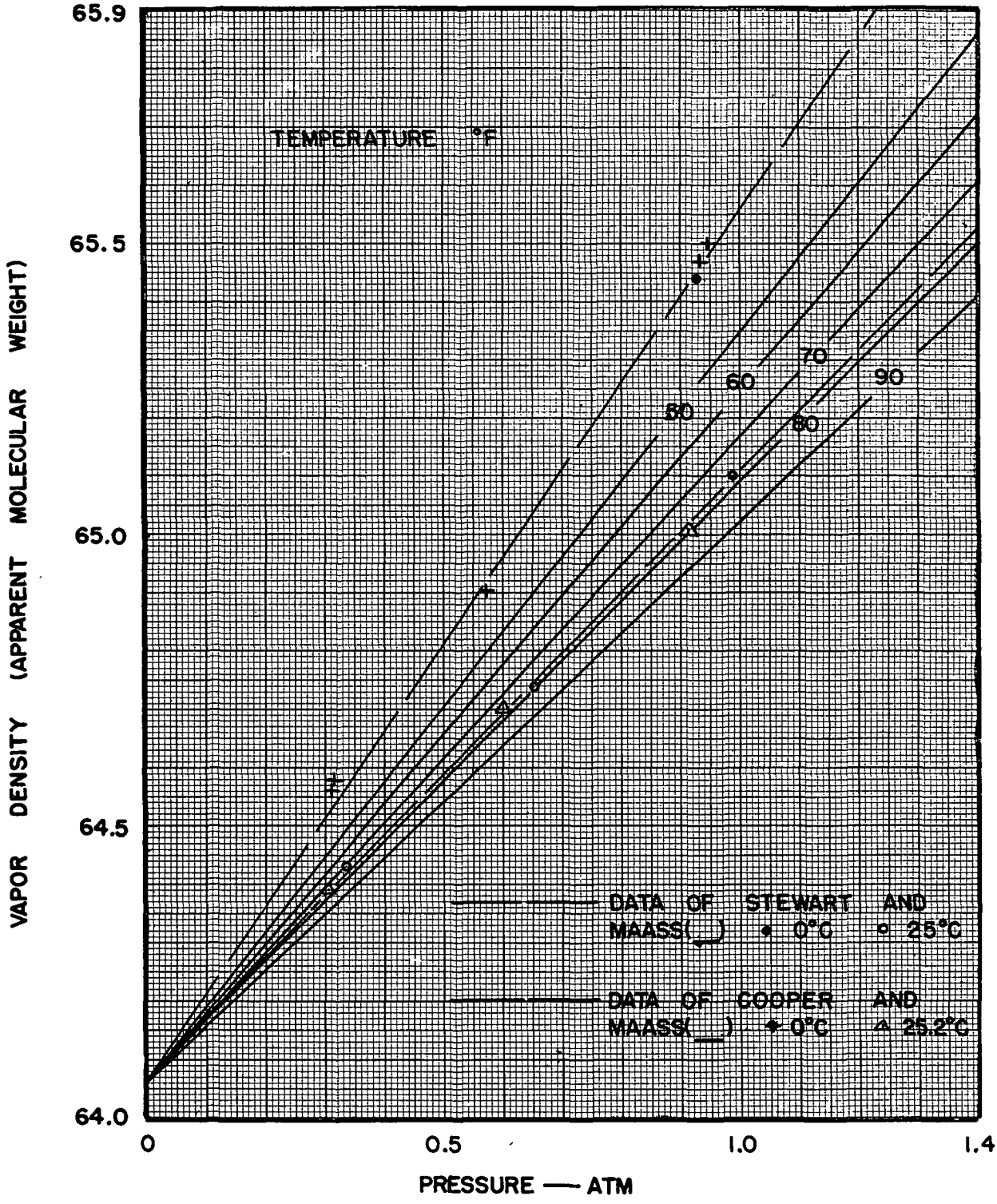

Figure 45. Vapor Density of Sulfur Dioxide as a Function of

Ordinate	0	1	2	3	4	5	6	7	8
$\underline{c}_e - \underline{c}$, x10^4	4.60	6.45	7.90	9.25	10.3	11.4	12.4	13.4	14.4
$1/(\underline{c}_e - \underline{c})$ x10^{-3}	2.18	1.55	1.27	1.08	0.970	0.875	0.803	0.745	0.696

The values are substituted into the Simpson's rule expression

$$\underline{A} = \underline{h}/3\ [(y_0 + y_8) + 4(y_1+y_3+y_5+y_7) + 2(y_2+y_4+y_6)]$$

where $\underline{h}/3 = 0.000122$

$\underline{A} = 0.316$

$\underline{L}/\Delta\underline{h} = 5000/62.3 \times 1.15 = 69.7$

$\underline{K}_L\underline{a} = (0.316)(69.7) = 22.0$

2. NORMAL COEFFICIENT—MEAN DRIVING FORCE BY USE OF LOG-MEAN

The log-mean driving force may be used only in those cases in which the operating and equilibrium lines are linear, or the approach to linearity is sufficiently close to cause only a small error. Run 251, illustrated above, will be recomputed using the log-mean method to show the mechanics of the computation and also a comparison of the results between the two.

$$\underline{K}_L\underline{a} = L/\rho\underline{h} \int_{\underline{c}_2}^{\underline{c}_1} d\underline{c}/\underline{c}_e - \underline{c} = \underline{L}/\rho\underline{h}\ (\underline{c}_1 - \underline{c}_2)/\text{log mean } \Delta\,\underline{c}$$

where the log-mean $\Delta\,\underline{c}$ is defined as $\dfrac{(\underline{c}_{2e} - \underline{c}_2) - (\underline{c}_{1e} - \underline{c}_1)}{\log_e \dfrac{(\underline{c}_{2e} - \underline{c}_2)}{(\underline{c}_{1e} - \underline{c}_1)}}$

$$\text{or } \frac{\Delta c_2 - \Delta c_1}{\log_e \frac{\Delta c_2}{\Delta c_1}} = \frac{0.00144 - 0.000460}{\log_e \frac{0.00144}{0.000460}} = \frac{0.000975}{1.14}$$

$$\text{log-mean } \Delta c = 0.000854$$

$$\frac{K}{L} a \frac{5000 \times 0.000292}{62.3 \times 0.000854 \times 1.15} = 23.9$$

3. NORMAL COEFFICIENT—ARITHMETIC MEAN DRIVING FORCE.

A study of the change in log-mean as a function of the ratio of the two values reveals that as the ratio approaches one, the log-mean approaches the simple arithmetic mean—in fact, below a ratio of about 1.3, the arithmetic mean can be more accurately determined than can the log-mean. At a ratio of 2 the log-mean and arithmetic mean differ by 4%. Above this ratio the error increases rapidly. In this thesis the arithmetic mean is employed in those cases where the ratio is 1.9 or less.

4. PSEUDOCOEFFICIENT

Since the unhydrolyzed portion of the acid-suppressed system follows Henry's law, the use of the log-mean (or arithmetic mean) is correct in all cases. The method of calculation follows example 2 above. The driving forces are computed on the basis of Figure 4.

TABLE XXII

CALIBRATION OF 0.46-INCH LIQUOR ORIFICE FOR MERCURY MANOMETER

(Figure 46)

A. Water Temperature 100°F.

Manometer Δh, cm.	L, lb./hr.ft.^{2}
0.70	1,960
1.90	3,240
3.15	4,210
3.70	4,640
5.95	5,720
7.15	6,310
9.85	7,560
11.90	8,140
14.20	9,020
18.40	10,000
22.30	11,000
30.70	12,900

B. Water temperature 53°F.

Manometer Δh, cm.	L, lb./hr.ft.^{2}
3.80	4,700
6.50	6,000
20.00	10,600
30.00	12,900

TABLE XXIII

CALIBRATION OF 0.46-INCH LIQUOR ORIFICE FOR CARBON TETRACHLORIDE MANOMETER

(Figure 46)

Water Temperature 60°F.

Manometer Δh, cm.	L, lbs./hr.ft.^{2}
4.2	1,068
11.2	1,753
11.2	2,060
25.5	2,650
32.5	2,980
33.8	3,030
42.6	3,370
50.6	3,710
64.7	4,210
94.3	5,020
114.5	5,510

TABLE XXIV

CALIBRATION OF SQUARE-EDGED GAS ORIFICE PLATES

(Figure 47)

0.50-inch Orifice		0.91-inch Orifice		1.40-inch Orifice	
Manometer Δh, ft. of gas	Volume Rate of Flow, cu.ft./hr.ft.^{2}	Manometer Δh, ft. of gas	Volume Rate of Flow, cu.ft./hr.ft.^{2}	Manometer Δh, ft. of gas	Volume Rate of Flow, cu.ft./hr.ft.^{2}
97.16	655	92.93	2160	69.17	5,270
136.8	816	146.8	2840	251.5	9,560
208.1	1036	202.0	3334	147.4	6,630
291.1	1206	264.7	3870	199.7	8,640
384.4	1407	331.8	4315	344.8	11,520
433.3	1502	407.3	4890	394.9	12,380
597.6	2050	480.1	5440	531.4	15,050
687.3	1925	569.2	6000		
		650.6	6385		
		705.3	6580		

NOTATION AND SYMBOLS USED

a	the effective interfacial mass-transfer area of wetted packing in a packed tower, ft.^{2}/ft.^{3}
a'	an empirical constant
a_d	area of dry packing per unit volume, ft.^{2}/ft.^{3}
A	an empirical constant; as a subscript, the solute gas
A_p	area factor of tower packing used by Taecker and Hougen (12)
B	an empirical constant; as a subscript, the inert gas
c	concentration of solute in the liquid phase, lb.-mols./ft.^{3}
c_e	concentration of solute in the liquid phase in equilibrium with the partial pressure of the solute in the main body of the gas phase, lb.-mols./ft.^{3}
c_i	concentration of solute in the liquid phase at the gas-liquid phase interface, lb.-mols./ft.^{3}
c_o	the abscissal intercept of a straight-line fit of the equilibrium—solubility curve, lb.-mols./ft.^{3}
c_u	concentration of the unhydrolyzed or molecular portion of the solute, lb.-mol./ft.^{3}
Δc	the liquid-side driving force $(c_e - c)$ or $(c_i - c)$, lb.-mols/ft.^{3}
c_1	concentration of the solute in the exit liquor, lb.-mols./ft.^{3}
c_2	concentration of the solute in the inlet liquor, lb.-mols./ft.^{3}
C.D.R.	critical damping resistance, ohms
$\frac{dp_A}{dx_G}$	partial pressure gradient of diffusing gas over some length
D_G	molecular diffusivity of solute gas through air, ft.^{2}/hr.
D_L	molecular diffusivity of solute through liquid, ft.^{2}/hr.
e	base of the natural logarithms

NOTATION AND SYMBOLS USED (CONTINUED)

f_b	multiplying factor used in volumetric analysis of tower gas samples
F	a constant in the Stokes-Einstein equation
g	acceleration due to gravity, ft./sec.^{2}
G	average mass rate of flow of gas through tower, lb./hr.ft.^{2}
G_m	average molar rate of gas flow through tower, lb.-mols./hr.ft.^{2}
G'_m	molar rate of inert gas flow through tower, lb.-mols./hr.ft.^{2}
h	height of tower packing, ft.
$h_g a_h$	enthalpy gas-film transfer coefficient, B.t.u./hr.ft.^{2} Δ°F.
H	Henry's law constant defined as $H = c/p$, lb.-mols./ft.^{3} atm. c is total concentration of solute
H'	Henry's law constant defined as $H' = (c - c_o)/p$, lb.-mols./ft.^{3} atm. c is total concentration of solute
H_u	Henry's law constant defined as $H_u = c_u/p$, lb.-mols./ft.^{3} atm. c_u is concentration of unhydrolyzed or molecular solute
H_{OG}	height of an over-all gas-phase transfer unit, ft.
H_{OL}	height of an over-all liquid-phase transfer unit, ft.
H.T.U.	height of a transfer unit, ft.
k_G	gas-film coefficient, lb.-mols./hr.ft.^{2} atm.
$k_G a$	gas-film coefficient on a volume basis, lb.-mols./hr.ft.^{3} atm.
k_L	liquid-film coefficient, lb.-mols./hr.ft.^{2} unit Δc
$k_L a$	liquid-film coefficient on a volume basis, lb.-mols./hr.ft.^{3} unit Δc
$(k_L a)_n$	normal liquid-film coefficient on a volume basis lb.-mols./hr.ft.^{3} unit Δc
$(k_L a)_p$	pseudo liquid-film coefficient on a volume basis lb.-mols./hr.ft.^{3} unit Δc

NOTATION AND SYMBOLS USED (CONTINUED)

K	ionization constant for the dissociation of sulfurous acid; also kilo (as kilohms)
K_G	over-all gas-film coefficient, lb.-mols./hr.ft.^{2} atm.
$K_G a$	over-all gas-film coefficient on a volume basis, lb.-mols./hr. ft.^{3} atm.
K_L	over-all liquid-film coefficient, lb.-mols./hr.ft.^{2} unit Δc
$K_L a$	over-all liquid-film coefficient on a volume basis, lb.-mols./ hr.ft.^{3} unit Δc
K_I	first order reaction rate constant
L	rate of liquor flow through tower, lb./hr.ft.^{2}
m	an empirical constant
$(meq)_b$	milliequivalents of sulfur dioxide in volumetric analysis gas sample balloon
M	average molecular weight
n, n'	empirical constants
N_A	rate of diffusion of solute, lb.-mols./hr.ft.^{2}
$N_A a$	rate of diffusion of solute on a volume basis, lb.-mols/hr.ft.^{3}
N_{OG}	number of over-all gas-phase transfer units
N_{OL}	number of over-all liquid-phase transfer units
p	partial pressure of solute gas in gas phase, atm.
p_B	partial pressure of inert (nondiffusing) gas, atm.
p_{BM}	log-mean of inert gas partial pressure at gas-film boundaries, atm.
p_e	partial pressure of solute in equilibrium with the concentration of dissolved solute in the main body of the liquid phase, atm.
p_i	partial pressure of solute in the gas phase at the gas-liquid phase interface, atm.

NOTATION AND SYMBOLS USED (CONTINUED)

Δp	the gas-side driving force due to a partial pressure difference over the gas film, atm.
p_1	partial pressure of solute in the feed gas, atm.
p_2	partial pressure of solute in the exit gas, atm.
P	total pressure on the system, atm.
P_t	pressure of saturated tower gas sample, atm.
q	an empirical constant
r_G	gas-film resistance, the reciprocal of the gas-film coefficient, $H/k_G a$, hr.
r_L	liquid-film resistance, the reciprocal of the liquid-film coefficient, $1/k_L a$, hr.
r_L/R_L	fraction of total resistance to mass transfer residing in the liquid film
R	gas constant, ft.^{3} atm./lb.-mol. °R.
R_b	gas constant, liter-atm./g.-mol. °K.
R_L	over-all liquid-film resistance, the reciprocal of the over-all liquid film coefficient, $1/K_L a$, hr.
s	an empirical constant
t	temperature, °F. (unless otherwise specified)
t_1	temperature of feed gas, °F.
t_2	temperature of exit gas, °F.
T	absolute temperature, °R. (unless otherwise specified)
T_b	absolute temperature of volumetric gas sample, °K.
T_1	temperature of exit liquor, °F.
T_2	temperature of feed liquor, °F.

NOTATION AND SYMBOLS USED (CONTINUED)

tanh	the hyperbolic tangent value of the function
$\underline{V}$	volume of tower, ft.^{3}; also, linear velocity of gas, ft./sec.
$\underline{V}_b$	volume of sampling balloon, liter
$\frac{x'm'}{\underline{G}}$	a correcting factor introduced by Brownell and Katz (43) to correct for packing porosity and type of packing
$\underline{x}_G$	hypothetical thickness of gas film, ft.
$\underline{x}_L$	hypothetical thickness of liquid film, ft.
$\alpha, \beta, \gamma, \varepsilon$	empirical constants
η	relative viscosity compared to water
μ	viscosity, lb./ft.hr.
μA	microampere
π	total pressure on the system, atm.
ρ	density, lb./ft.^{3}

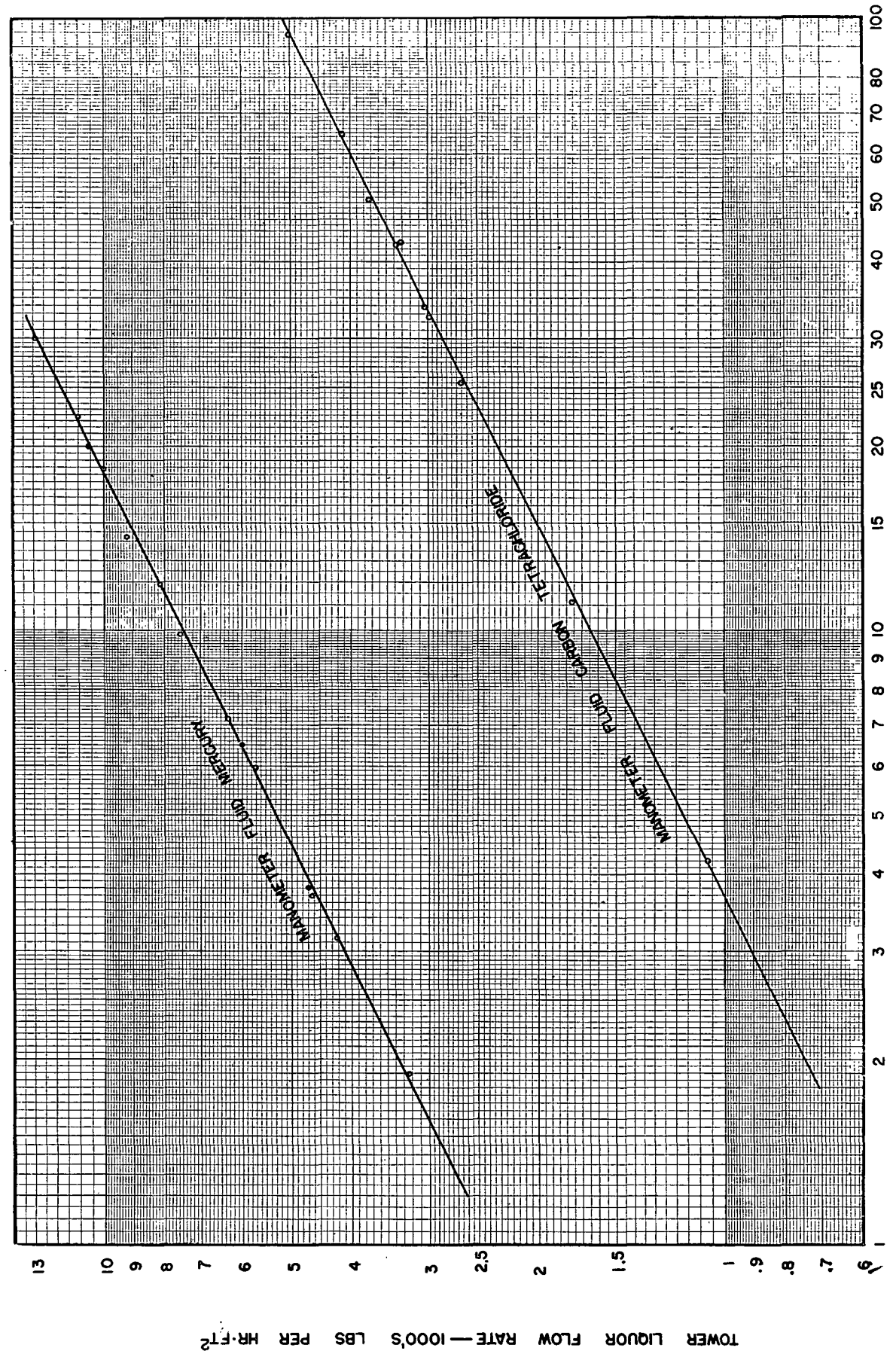

FIGURE 46. Calibration of 0.46-inch Liquor Orifice.

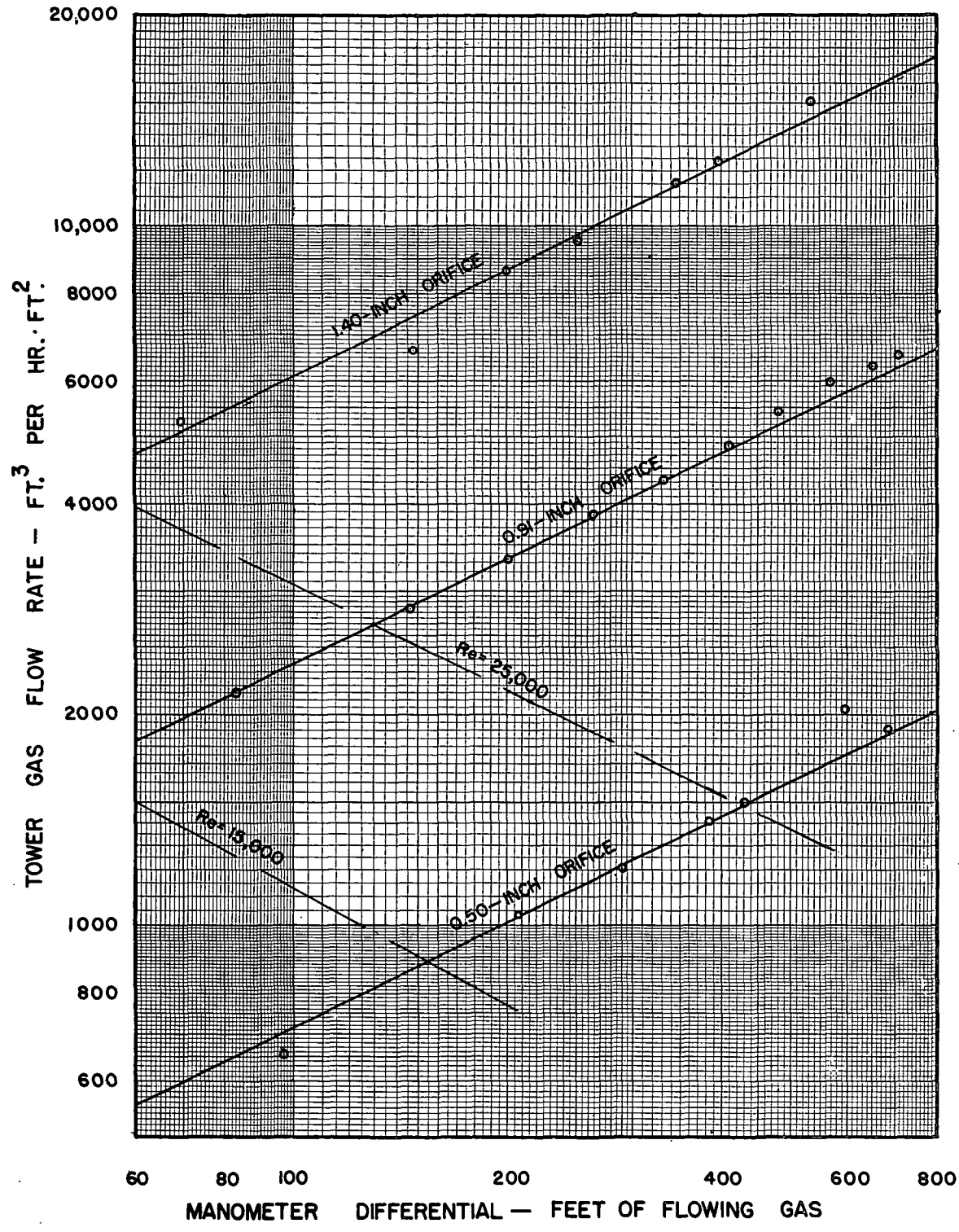

FIGURE 47. Calibration of Gas Orifice Plates.

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